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GEOPHYSICS

A Journal of General and Applied Geophysics

Published Quarterly by the
Society of Exploration Geophysicists

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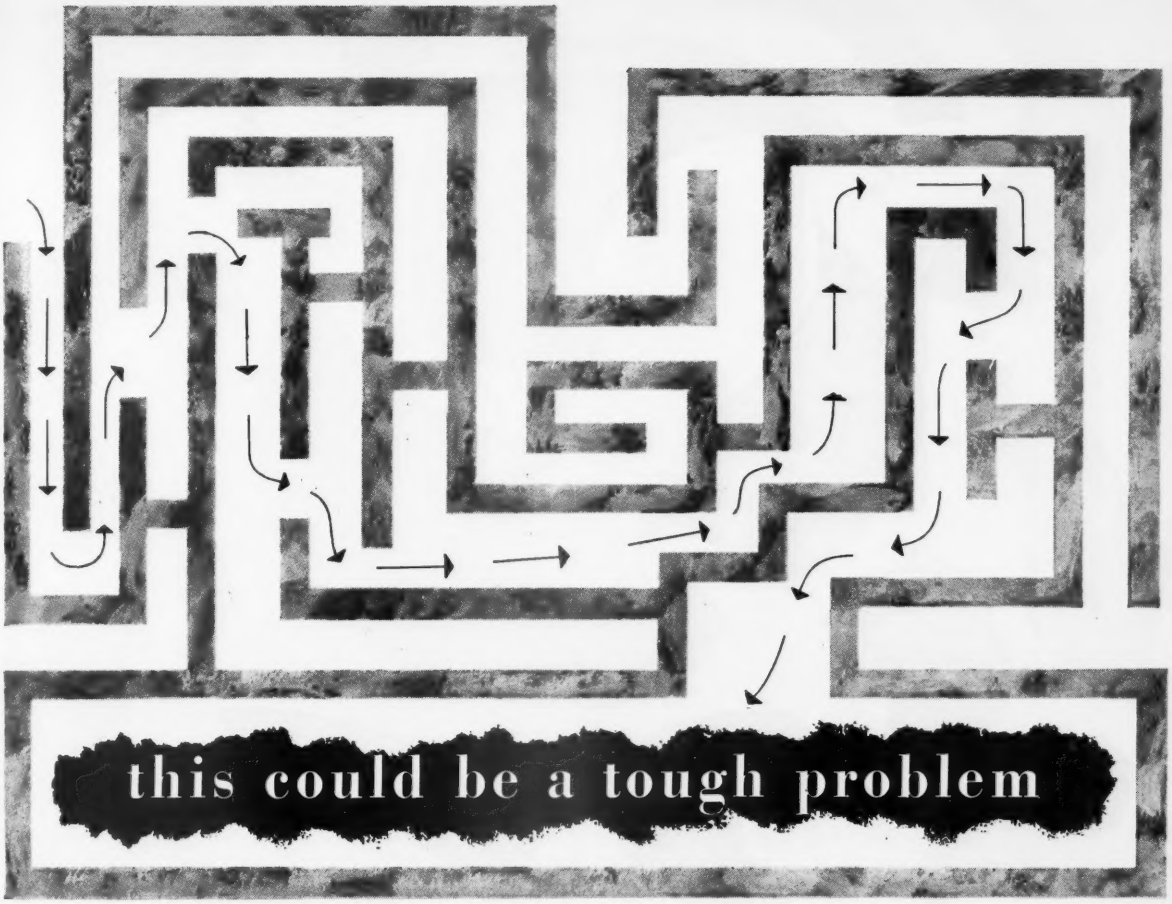

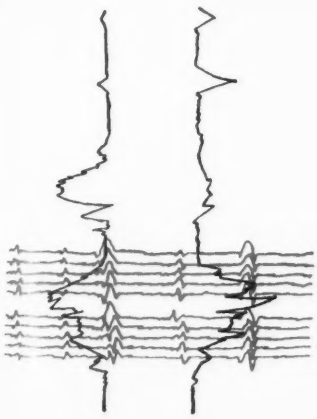

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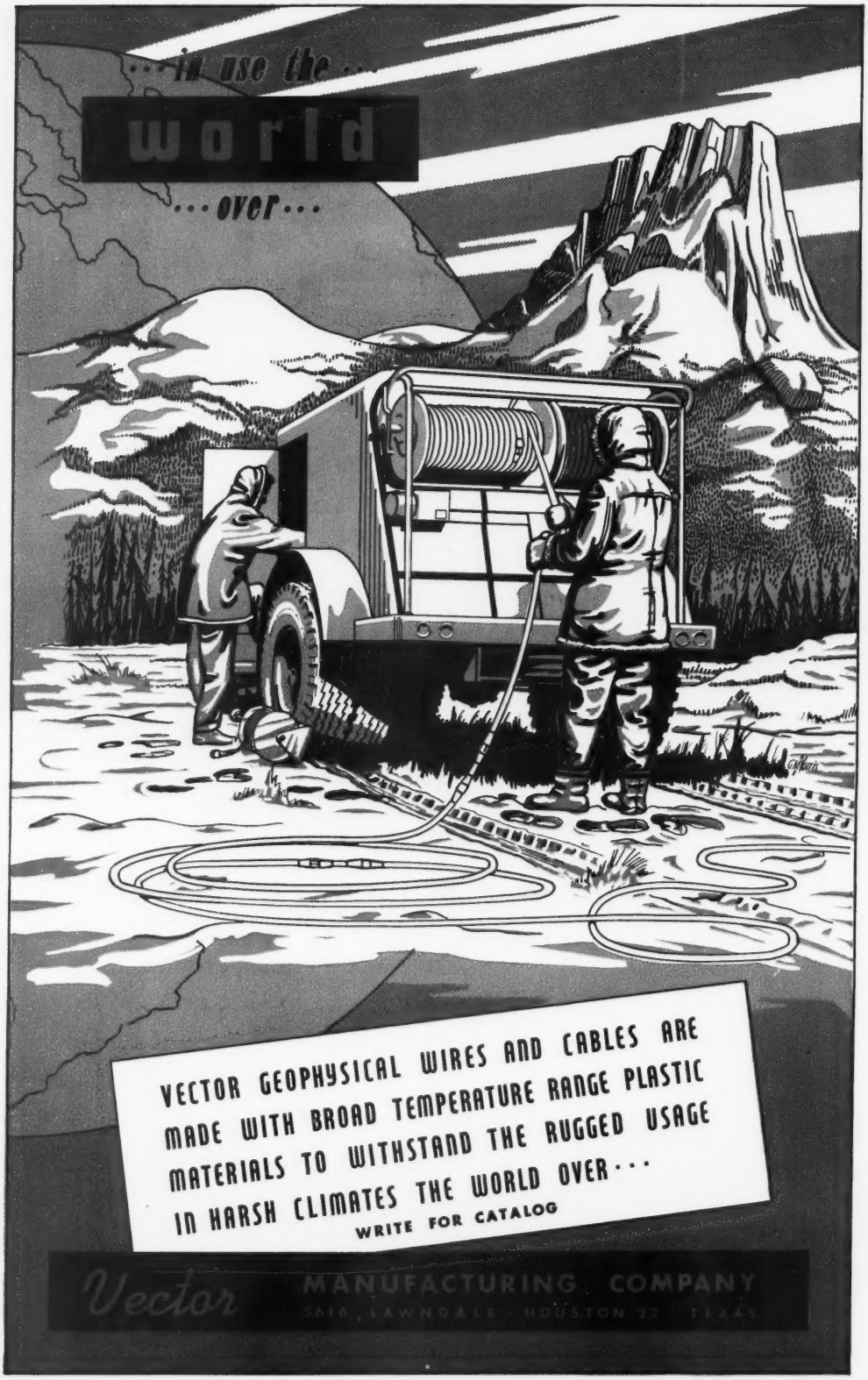
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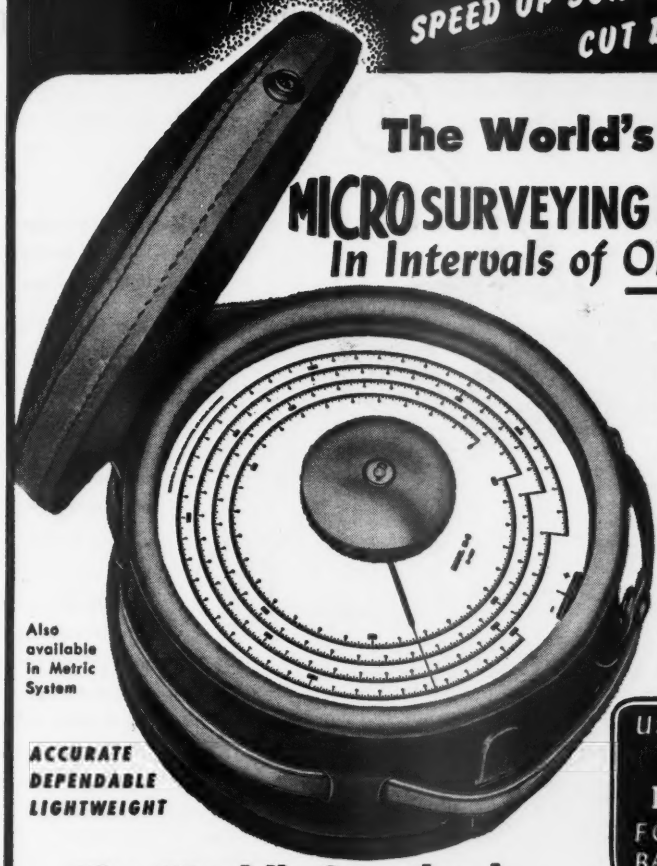

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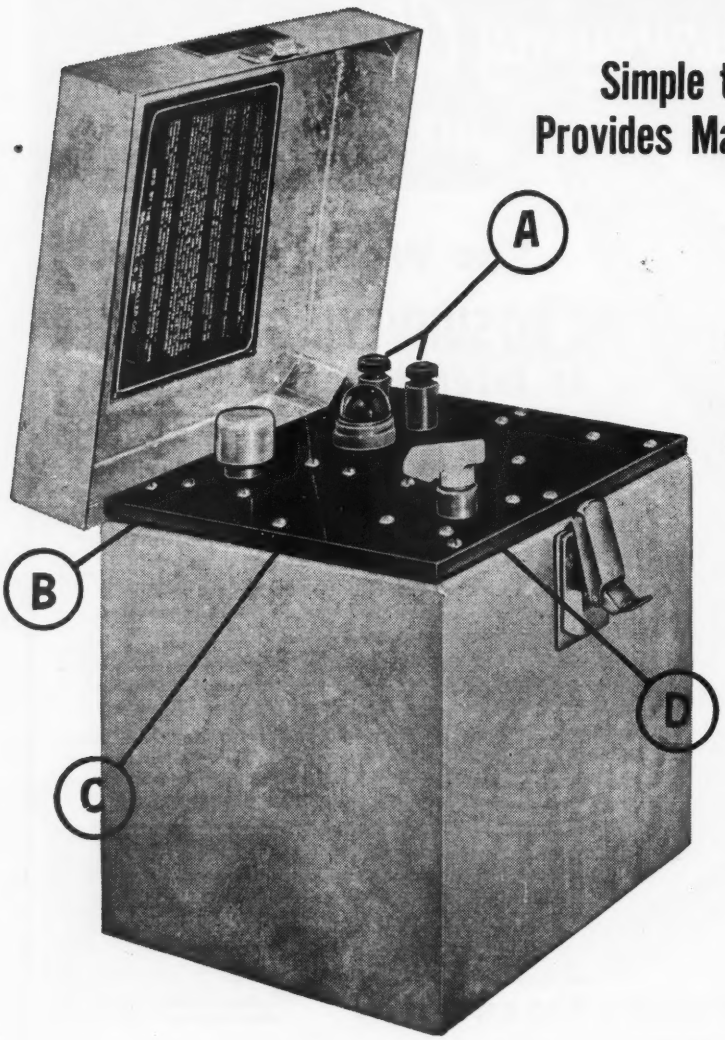

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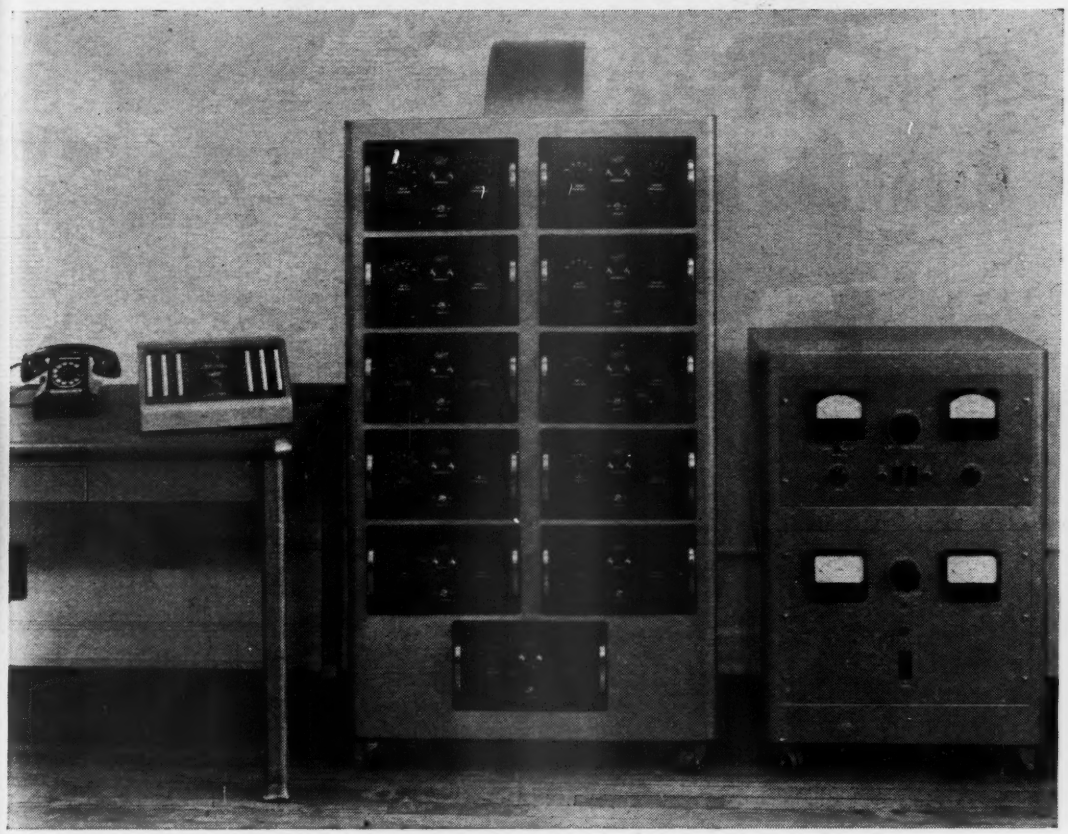

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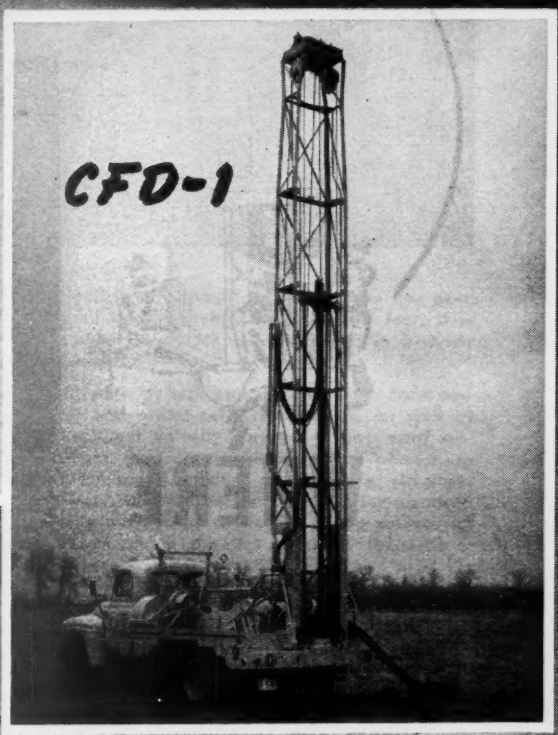

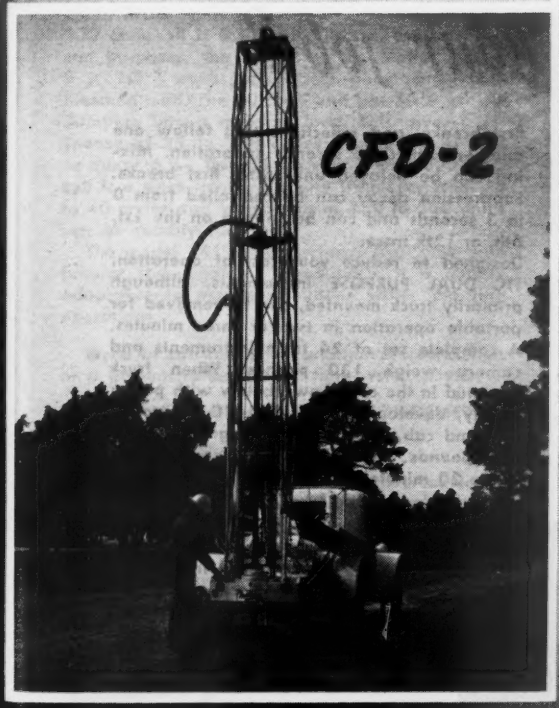

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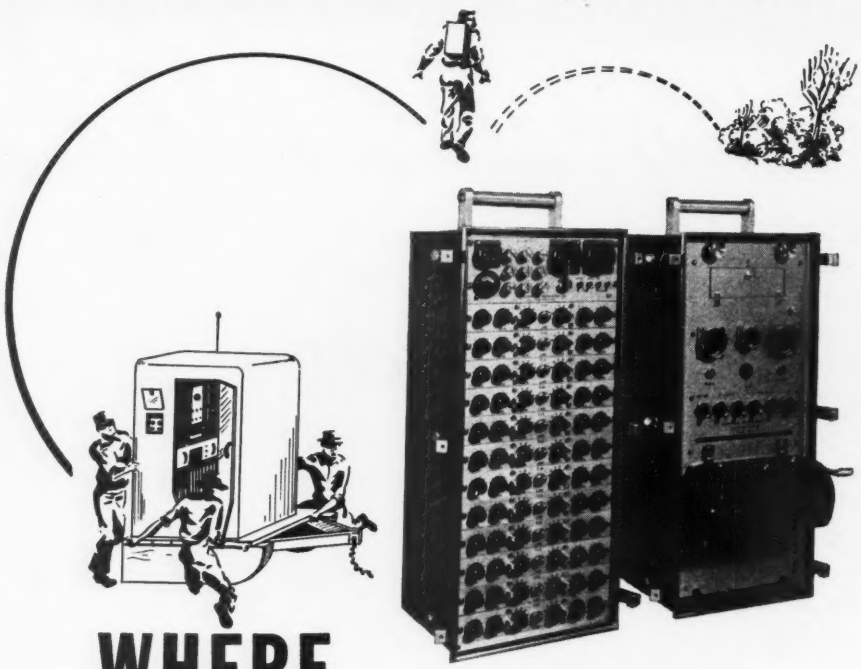

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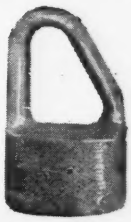

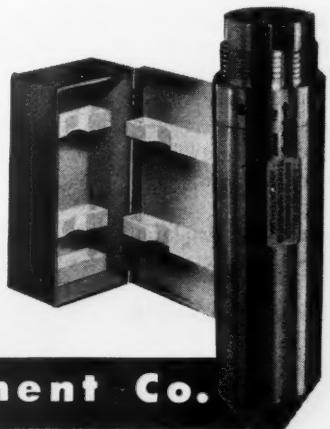

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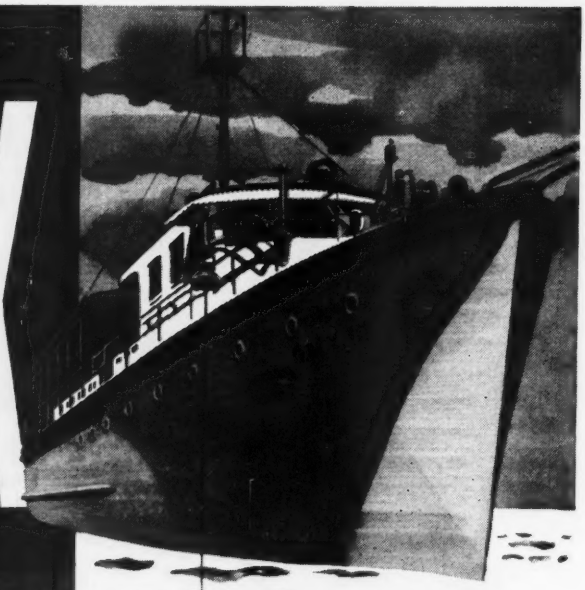

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VOLUME XVIII JULY, 1953 NUMBER 3

GEOPHYSICS

A Journal of General and Applied Geophysics

OUR HUMAN ASSETS IN GEOPHYSICS*

CURTIS H. JOHNSON†

The three societies represented here have a common purpose: oil-finding. In the pursuit of this purpose they may achieve many other incidental goals; make many far-reaching contributions to the broad fields of geology and geophysics, and even to the fields of physics and chemistry. But the prime purpose toward which the efforts of most of the members are directed is still oil-finding. On that we shall be judged.

In the pursuit of oil the important assets of geophysics, like those of geology, are its human assets. In a recent article[1] Wallace Pratt has used the term "oil-finder" to embrace geologists and geophysicists alike in the following statement: "Where oil is first found, in the final analysis, is in the minds of men. The undiscovered oil field exists only as an idea in the mind of some oil-finder. When no man any longer believes more oil is left to be found, no more oil fields will be discovered, but so long as a single oil-finder remains with a mental vision of a new oil field to cherish, along with freedom and incentive to explore, just so long new oil fields may continue to be discovered."

Levorsen[2] has even gone so far as to say that our instrumentation may be a hazard to oil-finding because too great a dependency on "mechanical crutches" may dull the ability of geologists or lessen their inclination to do "discovery thinking." However, thought breeds thought. It is the job of the geophysicist as an oil-finder to provide a buffer of thought between the geologist oil-finder and these so-called mechanical crutches. It is equally the job of the geophysicist to practice "discovery thinking" to qualify as an oil-finder.

* Address by the retiring President of the Society of Exploration Geophysicists at the joint meeting of the A.A.P.G., S.E.P.M. and S.E.G., March 24, 1953, Houston. Manuscript received by the Editor March 11, 1953.

† General Petroleum Corporation, Los Angeles. Now with Geophysical Service Inc., Dallas.

[1] Wallace E. Pratt, "Toward a Philosophy of Oil Finding," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 36, No. 12, December, 1952.

[2] A. I. Levorsen, "Discovery Thinking," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 27, No. 7, July, 1943.

Let us wipe out the misconception that the principal asset of geophysics is its instruments.

The geophysicist must be both the creator and the master of his machines. His instruments achieve nothing but what his human skill has built into them nor do they impart anything but what his human skill takes out of them.

Let us, then, take stock of our assets; see what they have done for us, what they can do for us in the future, and how we can nurture and expand them—realizing that they are all, in the final analysis, human assets.

The human beings comprising our profession have individual qualities that have made and will continue to make oil-finding a success. Let's consider some of these qualities as listed by some of our eminent writers, none of whom intended his list to be all-inclusive.

"Faith, persistence, the venture spirit and vision," says Pratt. "Acuity and experience," says Wyckoff. "Performance in spite of skepticism," says Morgan. "Ingenuity, industry, interest and common-sense," says Gilmour. Then, to complete the quotations but by no means exhaust the literature, Levorsen has emphasized the ability to do "creative geology," which we might broaden to include "creative geophysics" or creative thinking in general.

As selected, these quotations omit such obvious necessary qualities of an oil-finder as imagination, enthusiasm, curiosity and courage—courage to "stick out the neck"; courage to admit mistakes.

Underlying all these qualities and implemented by them must lie the urge—the drive—to discover. Without this drive all latent abilities are wasted. With it even the beginner becomes an oil-finder; the veteran's accomplishments astound.

But more homely qualities of our people must be counted among our assets—in fact, they are vital to our success. How much our success depends upon physical stamina; upon physical and mental prodigality. For twenty-one years I have been engaged in either geophysical instrument design or geophysical exploration, working with others of my kind. I recall the changing panorama in the background but always, in the foreground, a man or a group of men laboring far into the night; deriving the final step in that elusive equation; making that last vital instrumental check; taking that last important observation; picking that last fugitive reflection; or drawing that last all-important contour.

How many times in the past have I arrived at some small town at midnight to find it deserted save for other geophysical supervisors hurrying on their rounds—confident, like myself, that the party chief would be waiting to discuss his problems with unfailing cheerfulness and alertness. Such situations are routine and taken in stride.

What of the home life of our men? How can our men spend their energy so freely in the pursuit of oil—uproot themselves so frequently to invade new areas—without disrupting their homes? Here let me sing a paean of praise to our wives. It is long overdue and richly deserved. Men, we have not done them sufficient honor. Oil industry, you have not recognized them enough with your family

picnics, your group insurance, and the pictures in your company magazines. The best thing you have done is to keep their husbands happy and eager in their work—hence, we hope, happy and eager as husbands.

What other every-day virtues are essential to our success? Surely we depend upon common honesty and loyalty. We depend upon diligence and accuracy. We depend upon friendliness and courtesy.

Do we find all these virtues and the other qualities we have described in every member in our ranks? Let's not kid ourselves. We are not perfect. However, to the extent we possess them our chances for success increase. I do believe we have them to an unusual degree. People who don't have most of these qualities simply do not survive our rigors. There is a winnowing action which separates the grain from the chaff—a task which separates the men from the boys.

No less significant than the qualities which make oil-finders of individuals are the human assets we possess as a group.

Many of these are legacies from the past. Most of them we take for granted, but it is good sometimes to count our blessings and be thankful.

In the first place, we have inherited the scientific method upon which all our thinking is based and we have inherited a public acceptance of the scientific method as a respectable aspect of society. Can you imagine finding oil in an atmosphere of superstition and intolerance toward this method?

Secondly, we have grown at a time when the idea of a profession has been long established—a profession setting its own standards and providing a basis for cooperative understanding among its members. Our three societies sponsoring this meeting owe their existence to the fact that professions exist.

In the third place, we have inherited a confidence born of the past achievements of men in other sciences. As scientists we have been handed down a tradition and a habit of success.

Finally, and perhaps most importantly, we have inherited, in our part of the world, at least, a free society in which to do our work, freedom to think and say what we please—to freely exchange ideas, freedom to come and go—to let our search for oil carry us where it will, freedom to direct or expand our investigations along paths of our choosing. We have the immeasurable benefit of working under a system of free enterprise and free industrial expansion based on a free market.

We dare not take all this freedom for granted. It is a precious thing which must be tended carefully to live. Our preoccupation with our science—with oil-finding itself—must not prevent our participation as good citizens in every activity which will keep us in the light of freedom.

Our human assets are many and varied, but along with them we are also heirs to all the usual human faults which we must school ourselves to avoid. Among the worst of these are complacency and self-satisfaction, skepticism and prejudice.

The old-timers among us remember a modification of the seismic method

which was proposed and provoked great discussion twenty years ago. This was essentially a proposal to record unmixed, broad-frequency seismograms in reproducible form—thereafter reproducing them with as many choices of mixing and frequency limitation as the mind could conceive. In retrospect it would seem that we exhibited all the above human faults in rejecting this proposal, for today, twenty years later, the principle is being widely accepted and there is a rush to acquire equipment and operational experience with the method.

Based on this experience, where a twenty-year period elapsed between a rejected proposal and final acceptance, one might make this prediction:

"Twenty years after its cold reception in 1940, Geochemistry will be revived and will receive wide acceptance as an oil-finding tool in 1960."

In my term of office I have had the opportunity of becoming very close to the men of our profession. We are rich in human assets. Let us realize that all our assets are human, and so take full responsibility in our task rather than place it on the instrument or machine. Let us strive to put this idea across to industry management that our men may achieve dignity and rewards to spur them on. Let us sell this idea to people as a whole that we may receive the sympathy and cooperation of Society. And let us do our part in Society to insure the liberty we now enjoy.

And let us not forget that we, as humans, have failings which are not assets in oil-finding or any other form of endeavor.

Our course of action is clear. We must recognize and strive to overcome our human shortcomings, and we must nurture, expand and utilize to the fullest all our human assets. Only thus will oil continue to be found.

GEOPHYSICAL ACTIVITY IN 1952*

E. A. ECKHARDT†

GEOPHYSICAL ACTIVITY IN THE OIL INDUSTRY

Geophysical activity during 1952 reached a new all-time high. On the basis of incomplete reports, the full time services of 948 crews were utilized the world over last year, an increase of 157 crews over 1951. The 9,801 crew-months of seismograph work in the U. S. and Canada alone exceeded the 9,549 crew-month world total of such work in 1951. There was a slight decrease in gravity operations from 1,526 crew-months in 1951 to 1,502 crew-months in 1952. The reports received on magnetometer activity seem to be neither complete nor reliable, and no attempt to estimate a trend seems justified.

The exploration results appear to have fallen well below the preliminary estimates. The total liquid hydrocarbon reserves proved during 1952 were estimated by A.P.I. to be about 3.30 billion barrels. If we deduct the 1952 production of 2.55 billion barrels, the net addition to reserves was only 750,000 million barrels, which was lower than it was for any year since 1947.

Although U. S. reserves at the beginning of this year stood at an all-time high of 32.96 billions of barrels of liquid hydrocarbons, it is to be noted that this represents only 12.9 years of supply at last year's rate of production. In 1929, U. S. production first exceeded one billion barrels, and in 1952 it was, for the first time, greater than 2.5 billion barrels. In this interval reserves fluctuated between a minimum of 11.9 years of supply at current annual rates of production to a maximum of 15.7 years. The average over this period was 13.4 years. The magnitude of our present reserves, though of record proportions, is not so when expressed in terms of years of supply at current production rates, being below the average for the last 23 years. In fact, the ratio of total reserves to annual production seems to be less for the U. S. than for any country or area which produces as much as 1% of the world's oil. The supply-demand relationship appears to be currently causing the industry some concern, but in this connection it may be well to remember that in terms of years of supply present reserves are low rather than high.

The month-by-month fluctuation of both seismograph and gravity operations in the U. S. is shown for the 1942–1952 period in Figure 1. The most striking feature of this picture is the rapid rise of seismograph activity which began very early in 1950 and culminated in October of last year. This rise carried from a low of

* Report of the Committee on Geophysical Activity of the Society of Exploration Geophysicists. The members of this committee are A. A. Brant, Herbert Hoover, Jr., R. Vajk and E. A. Eckhardt, Chairman. This report was presented at the Houston meeting of the Society, March 23, 1953. Manuscript received by the Editor April 17, 1953.

† Gulf Research & Development Company, Pittsburgh, Pa.

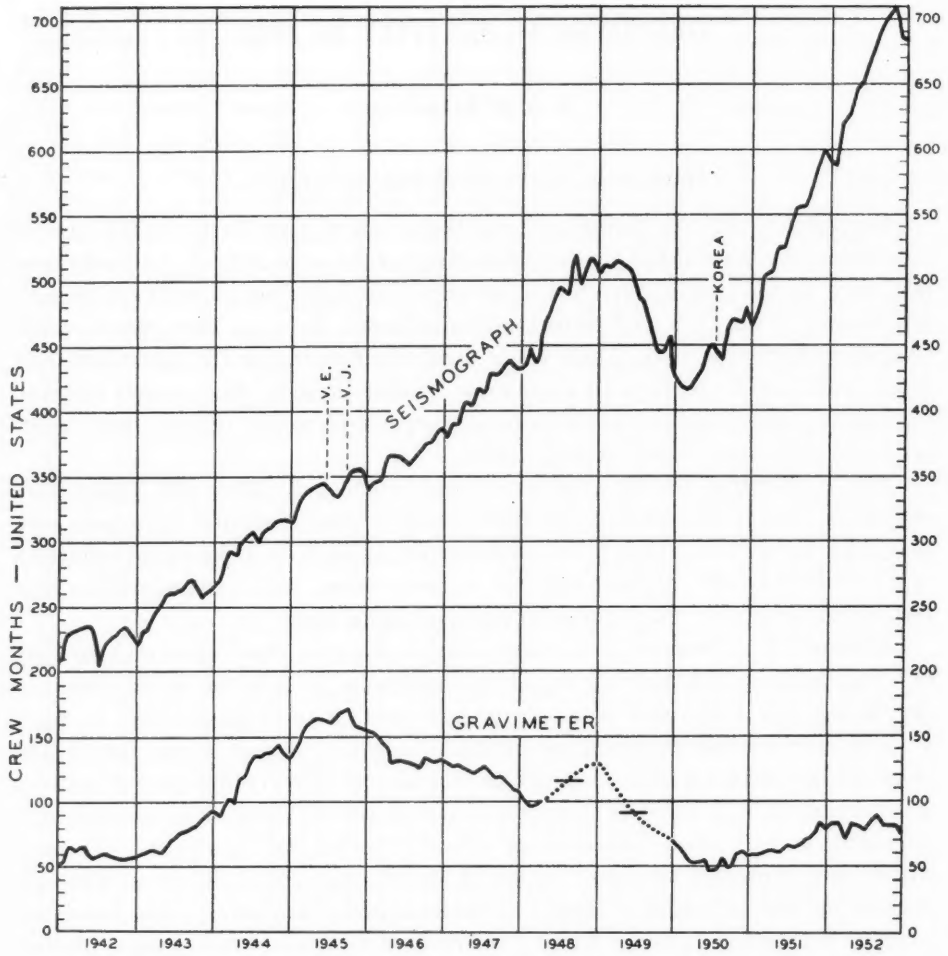


FIG. 1. Monthly variation in seismograph and gravimeter crew months in the U. S.

417 crews in 1950 to a high of 710 crews in 1952, representing an increase of about 70% over a period of less than three years. By January of this year, 1953, the number of crews had dropped to 641, a drop of less than 10%, possibly indicating that we are currently experiencing the kind of adjustment which was encountered in 1949. Related factors are hardly such, at this time, to justify the more pessimistic view that the history of 1937–1941 may be repeated.

The gravity graph in Figure 1 shows that these operations of last year in the U. S. fluctuated about the highest level reached during the preceding one. The 1952 activity came to a total of 965 crew months against 802 for 1951, an increase of 20%.

The geographic distribution of the 1952 U. S. seismograph operations is shown in Figure 2. For the first time since these reports were initiated six years ago,

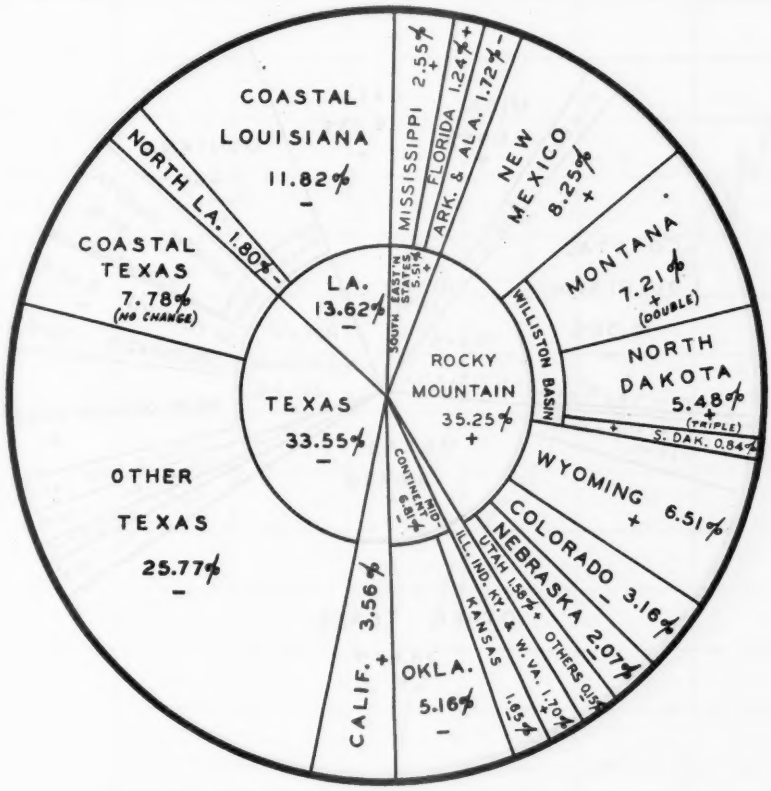


FIG. 2. Distribution of 1952 seismograph operations in the U. S.

Texas and Louisiana together account for less than one-half of the total activity. The concentration of work in the Rocky Mountain states, and more particularly in the Williston Basin, is evident in the chart. Table I is presented to give addi-

TABLE I

SEISMOGRAPH CREW MONTHS IN THE U. S.

State	1951	1952	Change
Texas	2,574	2,670	+ 3.7%
Louisiana	1,041	1,083	+ 4.0%
Mississippi	148	203	+ 37.2%
Oklahoma	371	411	+ 10.8%
New Mexico	496	657	+ 32.5%
Colorado	297	252	− 15.1%
Wyoming	317	519	+ 63.7%
Montana	255	574	+125.1%
N. Dakota	122	436	+257.4%
California	208	283	+ 36.1%
Other	708	870	+ 21.5%
Total	6,537	7,958	+ 21.7%

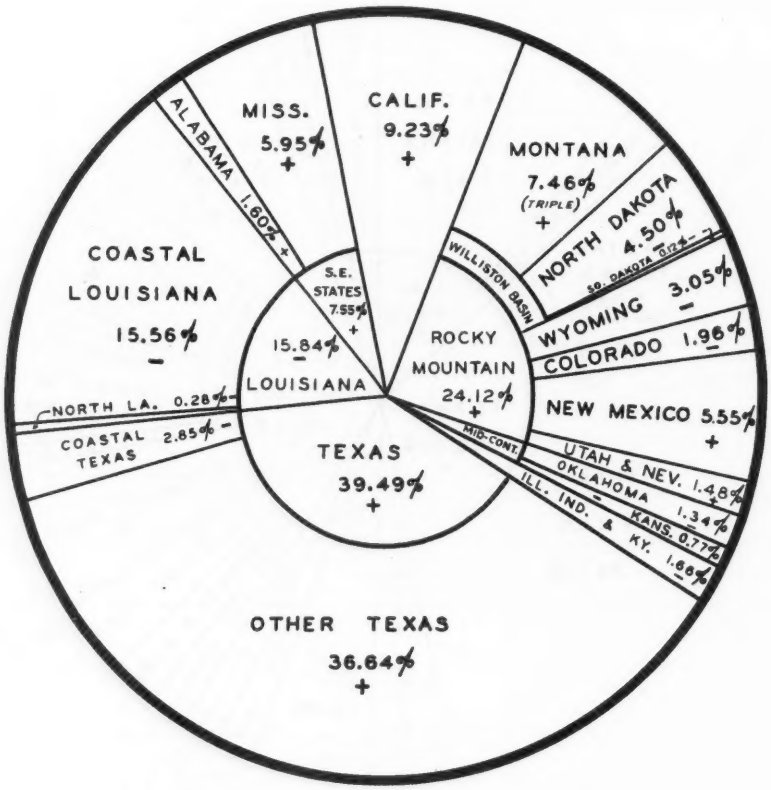


FIG. 3. Distribution of 1952 gravimeter operations in the U. S.

tional information concerning the growth and shifts of these activities. The table shows that the increased volume of 1952 was largely concentrated in the Williston Basin and adjacent areas, and that this concentration resulted in decreased activity only in Colorado.

TABLE II

GRAVITY CREW MONTHS IN THE U. S.

State	1951	1952	Change
Texas	294	381	+ 30%
Louisiana	192	153	− 20%
Mississippi	15	57	+280%
Oklahoma	28	13	− 54%
New Mexico	36	54	+ 50%
Colorado	35	19	− 46%
Wyoming	43	30	− 30%
Montana	17	72	+320%
N. Dakota	39	43	+ 10%
California	43	89	+107%
Other	60	54	− 10%
Total	802	965	+ 20%

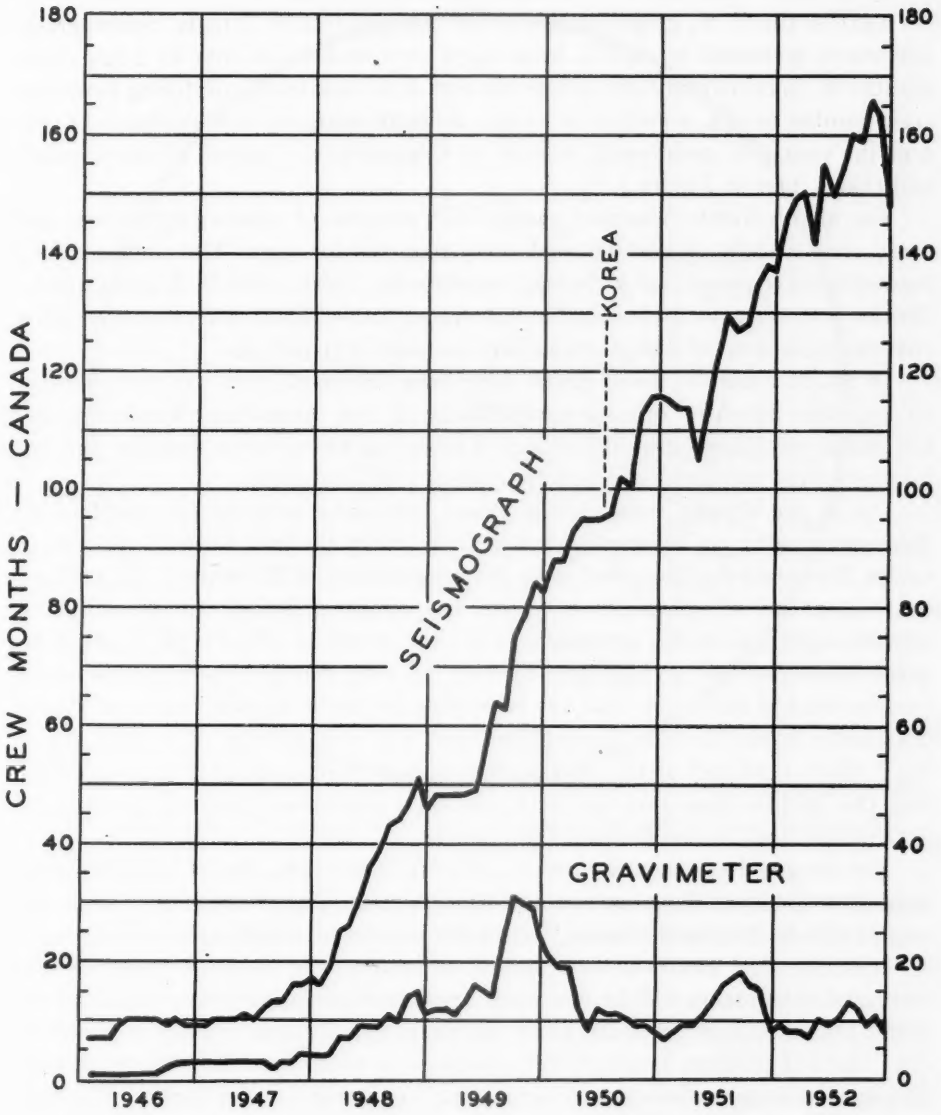


FIG. 4. Monthly variation in seismograph and gravimeter crew-months in Canada.

The areal distribution of 1952 U. S. gravimeter operations is shown by Figure 3. As in all previous reports of this series, the two states of Texas and Louisiana accounted for more than half of the year's work. The distributional changes from the preceding year were pronounced and are indicated in Table II. There were increases in six and decreases in four of the states listed. The increases were greatest percentagewise in Montana and Mississippi, and the decreases largest in Oklahoma and Colorado. There was an over-all increase of approximately 20%.

Next to the U. S., geophysical activity was greatest in Canada. Seismograph operations increased by 24.6% from 1,479 crew-months in 1951 to 1,843 crew-months in 1952. Gravity operations showed a reverse trend, declining from 147 crew-months to 114, a decline of 22.4%. Enough data are now available to present the course of geophysical activity in Canada over a period of seven years, and this is done in Figure 4.

For all of North America, 10,049 crew-months of seismograph work and 1,127 crew-months of gravity work were reported for 1952. The corresponding figures for 1951 were 8,248 and 1,024, respectively. Next to the U. S. and Canada, Mexico was the principal contributor to these totals. There was, however, little change in the level of operations in Mexico from 1951 to 1952.

In South America, seismograph operations increased from 349 crew-months to 459, the increases occurring principally in the Argentine, Venezuela and Colombia. Gravity operations increased from 114 to 158 crew-months, and the increases were accounted for largely by Peru and Venezuela.

Up to the closing time of this report, the data received for the Eastern Hemisphere were not sufficiently complete to justify the presentation of charts or tables. However, data received since the presentation of this report at the Houston convention substantially complete the picture. Seismograph activity decreased slightly from 894 crew-months in 1951 to 858 in 1952. Of the latter, Germany accounted for 349 and Italy for 106. All told, Europe was the scene of 619 crew-months of this work, and 171 were done in Africa. Gravity work decreased drastically in the Eastern Hemisphere from 337 crew-months in 1951 to 217 in 1952. More than half of the 1952 work was done in Europe (121 crew-months), and the Middle East was the next ranking contributor. Over-all, geophysical activity declined in the Eastern Hemisphere.

For the geophysical work done in 1952 for its account, the oil industry probably spent between $350,000,000 and $400,000,000. The increase over 1951 was largely due to increased volume, but partly also to increased unit costs.

It is clear that whatever the economic climate may be in the next year or two, increased exploration will be necessary because of the inevitably increasing demand for petroleum products. Over the years geophysical activity is bound to rise. The big problem faced by the operators is manpower. For the most part, geophysical organizations are concentrating on getting a larger portion of college graduating classes. There is a growing realization that more than this will be required.

The development of our natural resources is basic to the well being of our economy. Yet the percentage of high school students who receive any kind of training in the earth sciences has been decreasing continuously and markedly in the last 50 years. It was nearly 30% in 1900. It is a fraction of 1% today. Since the interests of young men are directed to a considerable extent before they arrive at college, this tends to minimize the college enrollment in earth science subjects.

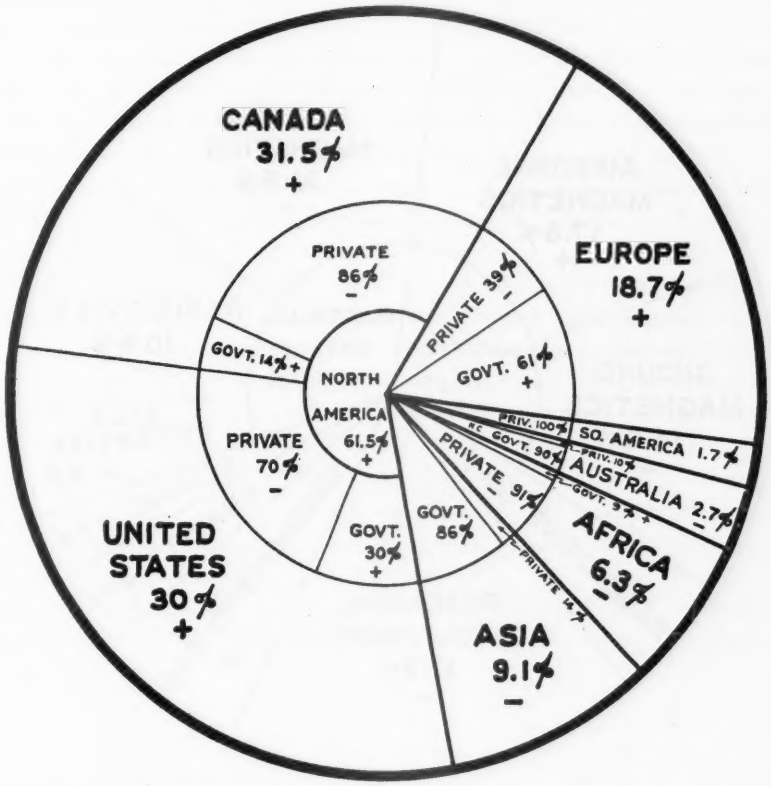


FIG. 5. World distribution of geophysical activity in mining by areas in 1952.—Professional man-month basis.

Dr. H. Cloos has dealt with this subject in a recent issue of the News Letter of the American Geological Institute. High school students must be made familiar with the earth sciences, job opportunities they offer, and their importance. This is a natural function for the A.G.I., and the manpower problems of geophysical operators are likely to receive most effective attention through their support of the Institute.

It is appropriate to pay tribute to the technical press which serves the oil industry and which has afforded much valuable information which has provided background for this report. Probably no industry is better served by its technical press than is the oil industry.

GEOPHYSICAL ACTIVITY IN THE MINING INDUSTRY

The mining industry reports that in 1952 it spent well over five million dollars for its field operations, geophysical research and development. This rather substantial increase over the 3.5 million dollars reported for 1951 is largely due to the reported data being more complete but, in part, also because of a real increase

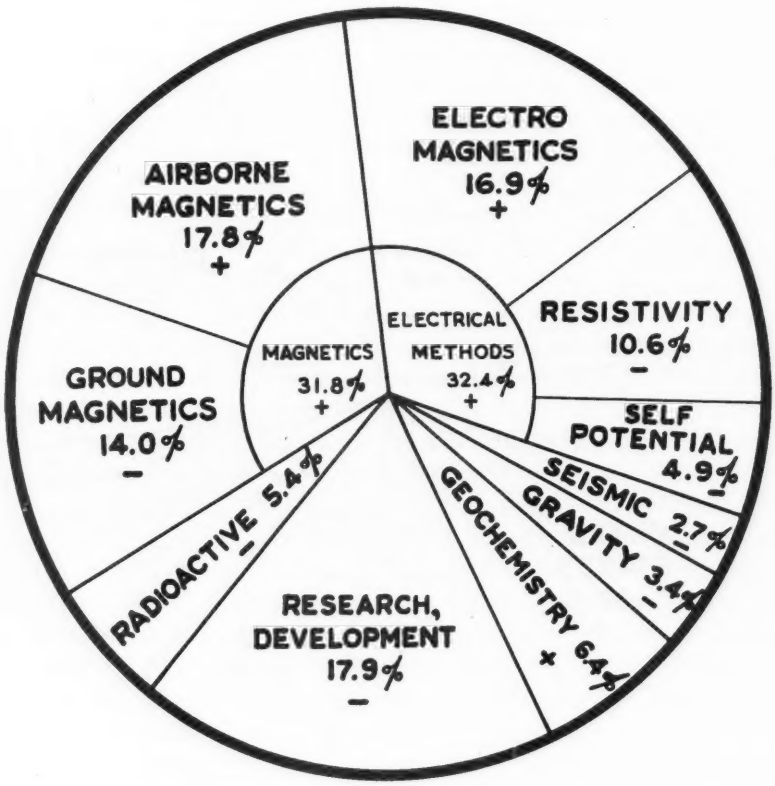


FIG. 6. World distribution of geophysical work in mining by methods for 1952.—Professional man-month basis.

in volume. It is estimated that the work reported represents about 70% of that which was done. On that basis, mining industry expenditures for geophysical work in 1952 were of the order of 7.5 million dollars.

The geographic distribution of last year's geophysical operations for mining companies is shown in Figure 5. About 61.5% of this work was done in Canada and the U. S. As in the preceding year, the volume of work in Canada was greater than in the U. S., but the difference between the two countries was substantially reduced. Europe's effort was next in order of magnitude, accounting for 18.7% of the total as against 14.6% in 1951. Some work in 1952 is reported from South America. The last previous report from this area was for 1948.

It is noted with regret that the ratio of private to government expenditures decreased slightly last year. This was true even in those areas where the private enterprise system finds its staunchest support. It is a trend which needs careful consideration by the industry.

The distribution by methods in 1952 is presented in Figure 6. This chart shows some marked changes as compared to 1951. The use of magnetic methods

increased materially last year and more particularly that of airborne surveys. Nevertheless, the total for the electric methods of all kinds slightly exceeded that for magnetics. Airborne magnetometer surveys accounted for the most man-hours and the largest expenditures. In addition, airborne electromagnetic and radioactivity surveys made sizable contributions to the total activity. Mining geophysics has become airborne to an extent not anticipated even a few years ago. Whether this is a transient phenomenon or the substantial beginning of a trend remains to be seen.

The utility of the geophysical activity data for both the oil and mining industries, but particularly for the latter, is still impaired by the lack of suitable measuring units. Improvement in these is possible and is important if trends are to be reliably evaluated. For example, some reports received list magnetometer crew-months irrespective of whether ground crews or airborne crews are involved. The difference in cost and accomplishment is, of course, considerable. The relationship of professional man-hours to the over-all operation also covers a considerable range. In any event, it would be helpful if those contributing information to the compiling committee would specify ground and airborne surveys separately.

Thanks are gratefully extended to the many people who have contributed data and to others who have been helpful in putting them into a form suitable for this report.

GEOPHYSICAL PROGRESS*

HENRY C. CORTES†

ABSTRACT

Histories or reviews covering the period from 1922, the first year of petroleum geophysics in the United States, to 1940 were ably presented by Eckhardt, Macelwane and Weatherby at the Society of Exploration Geophysicists' Annual Meeting of the latter year. This paper deals mainly with advances in geophysics since 1940.

Marked progress has been made in the amount of geophysical activity, in the number of new oil fields discovered per year based wholly or partially on geophysics, in geophysical techniques, and in education. Improvements in instrumentation, field operational procedures, and interpretation methods have steadily increased the usefulness of the three major methods—seismic, gravity, and magnetic. The development of the aerial magnetometer, especially, and the underwater gravimeter represent notable achievements. These developments have made possible the extension of geophysical activity offshore, and in many other areas previously considered inaccessible. Advances have also been made in logging, particularly in the radioactivity type, geochemistry and electrical prospecting.

Research, both fundamental and applied, is being conducted on a greater scale now than in 1940 or prior thereto. Increased geological-geophysical coordination has led to better appreciation and utilization of the geophysical methods and has resulted in the discovery of important oil and gas reserves.

Novel or more direct oil finding methods may possibly be discovered or perfected. It is more probable, however, that the future of exploration geophysics will be primarily in the continual refinement of the present known methods. Advances in exploration geophysics and geology, along with teamwork, should insure adequate production and reserves within the United States for a long period. This is predicated on our nation having competitive free enterprise, which has been responsible for the leadership of this country in oil finding, producing, transporting and refining techniques.

INTRODUCTION

Progress in exploration geophysics has been outstanding in the thirty years since its first use in the United States.

In 1940, at the Annual Meeting of the S.E.G., Eckhardt (1940), Macelwane (1940) and Weatherby (1940) gave reviews or histories which ably covered the introduction and progress of oil exploration geophysics to that date. Also, prior to 1940, there were other important historical contributions in the publications of the A.A.P.G., the A.I.M.M.E., Colorado School of Mines, and the S.E.G. Therefore, except to tie in earlier work, this paper will deal mainly with progress since 1940.

Geophysics brought in a new era of oil finding. The three principal geophysical methods, namely, seismic, gravimetric and magnetic, were all first used for petroleum exploration in the United States within a period of about one year. The impact of geophysics in the thirty years from 1922 to 1952 upon the development of the oil, gas and sulphur industries cannot be overestimated.

* Presented before a joint session of the A.A.P.G., S.E.P.M. and S.E.G. at their annual meetings in Houston, Texas March 25, 1953. Manuscript received by the Editor April 17, 1953.

† Magnolia Petroleum Co., Dallas, Texas. The author wishes to express his appreciation for the assistance given him by J. A. Lester, R. N. Gsell, J. W. Peters, and M. B. Dobrin, all of Magnolia Petroleum Co., in collecting material for this paper, and for the drafting of the illustrations by Mrs. Betty Richardson of the Geophysical Department, Magnolia Petroleum Co.

The effectiveness of these geophysical methods has been greatly increased by improvements in instrumentation, operational procedures and interpretation. Extensive research and development, supported mainly by the oil industry, has greatly strengthened the fundamental scientific base on which rests the future of geophysical exploration.

Since 1940, the mining industry has expanded its geophysical activity, particularly in research and development. Among the methods it employs are the magnetic, radioactivity, electric and geochemical. Airborne equipment has been used for the first two types of survey.

The number of geophysical crews is, in part, an indirect measure of progress. Statistics show an impressive growth since 1940 in total number of crews, in total expenditures, and in the number of discoveries based on geophysics combined with geology. As an example, annual reviews by Eckhardt (1948, 1953) show that the number of seismic crews in the United States increased from an average of about 190 in 1940 to an average of approximately 663 during 1952. For those same years the costs of those crews alone are estimated respectively at 30 million and 133 million dollars. Also, Lahee's annual figures show that geophysics or geophysics and geology combined were responsible for 122 new-field wildcat and new-pool wildcat discoveries in 1940 (see Lahee, 1941) as contrasted with 321 discoveries by new-field wildcats alone (i.e., not including new-pool wildcats) in 1952 (see Lahee, 1953).

GRAVITY EXPLORATION

In the field of gravity exploration, the torsion balance was introduced into this country in 1922. It was responsible for the discovery of numerous salt dome and other subsurface structures from 1922 up until 1940. Because of its slow operation and its unsuitability in rough terrain, the torsion balance was almost replaced by the gravimeter, or gravity meter, about 1940.

In 1930 the first gravity meter was used in the United States. During subsequent years, marked progress has been made in the development of this instrument, as illustrated in Figure 1. The early gravity meters, compared with present meters, weighed around 200 lbs., as against 5 or 6 lbs., and had an accuracy of 0.1 to 0.2 of a milligal at best, compared to the present instrument which approaches an accuracy of 0.02 of a milligal. The reading time has been reduced from around 20 minutes to less than 2 minutes. Increased interest in the Gulf of Mexico and its bays led to the development of gravity work over water-covered areas. The industry first witnessed the appearance of long tripods for use in relatively shallow waters. Later diving bells and the remote controlled gravity meter came into use in offshore waters. Several types of electronic position location systems were developed during World War II, and have been adopted for offshore gravity and seismic work, as well as for aerial magnetic surveys over land and water.

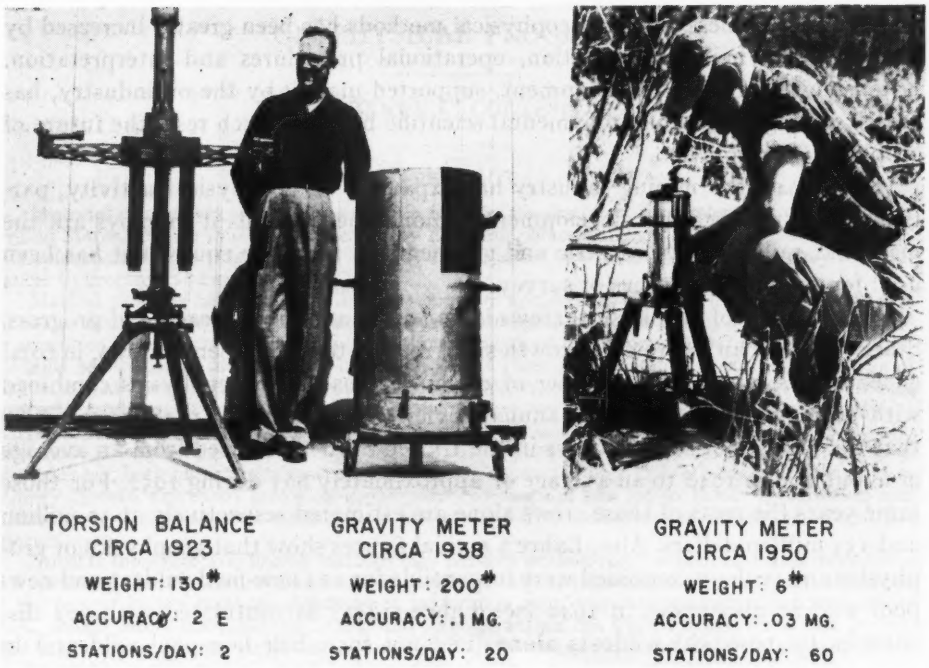


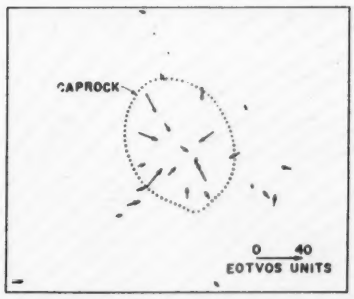
FIG. 1. Development of gravity measuring instruments between 1923 and 1950. The torsion balance is of the early Süss type. Picture of the 1950 instrument through courtesy of Houston Technical Laboratories.

GRAVITY INTERPRETATION

Gravity interpretation is subject to the inherent problems and limitations common to all "potential field" methods and, therefore, cannot yield a unique solution. However, continuous progress in the analysis of gravity data has led to better over-all interpretations, as is illustrated in Figure 2.

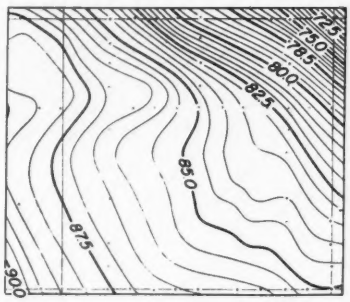
Residual and various derivative calculations, though used for some time, have received more recognition in recent years. These methods separate or amplify various components of the corrected gravity values (see Figure 3). With proper recognition of their applications and limitations, they may be used to resolve certain types of gravity anomalies. Calculations of the downward continuations of the gravity field, and other quantitative techniques, have been developed and are utilized in the analysis and interpretation of gravity data. Recently, various types of electronic computers have been used in quantitative and qualitative analysis of gravity data. These computers provide an extremely rapid, and, in some cases, a relatively cheap method of handling the numerous repetitive calculations common to such analysis.

Station density and accuracy of field surveys have increased, thus rendering the gravity data more adaptable to analysis, evaluation and interpretation. A



TORSION BALANCE SURVEY
NASH DOME, TEXAS
1924

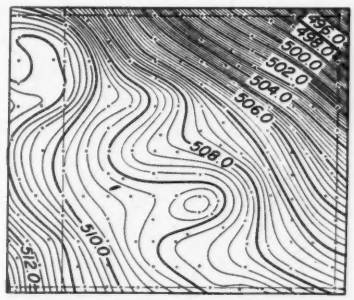
0 1 2
SCALE IN MILES



GRAVITY METER SURVEY
SOUTHERN OKLAHOMA
1940-41

CONTOUR INTERVAL 5 MG

0 1 2 3 4
SCALE IN MILES



GRAVITY METER SURVEY
SOUTHERN OKLAHOMA
1945-46

CONTOUR INTERVAL 2 MG.

0 1 2 3 4
SCALE IN MILES

FIG. 2. Improvements in gravity field and reduction techniques since 1924 as exemplified by torsion balance and gravity maps. The Nash shallow caprock salt dome, Brazoria County, Texas, was the first torsion balance discovery in the United States. The 1940 gravity meter map was contoured on half-milligal intervals from survey loops of 2 to 4 miles. The 1945–46 map, contoured on one-mile loops, shows a previously unrevealed anomaly.

considerable amount of geological, geophysical and density data are steadily being obtained, increasing our knowledge of the subsurface and furnishing the control which is required to offset the inherent ambiguity of gravity interpretations.

The gravity method has maintained its status as the most commonly used reconnaissance method.

MAGNETIC METHOD

The development of the airborne magnetometer, accomplished almost exclusively by an oil company around 1941, was a notable advance in the science of

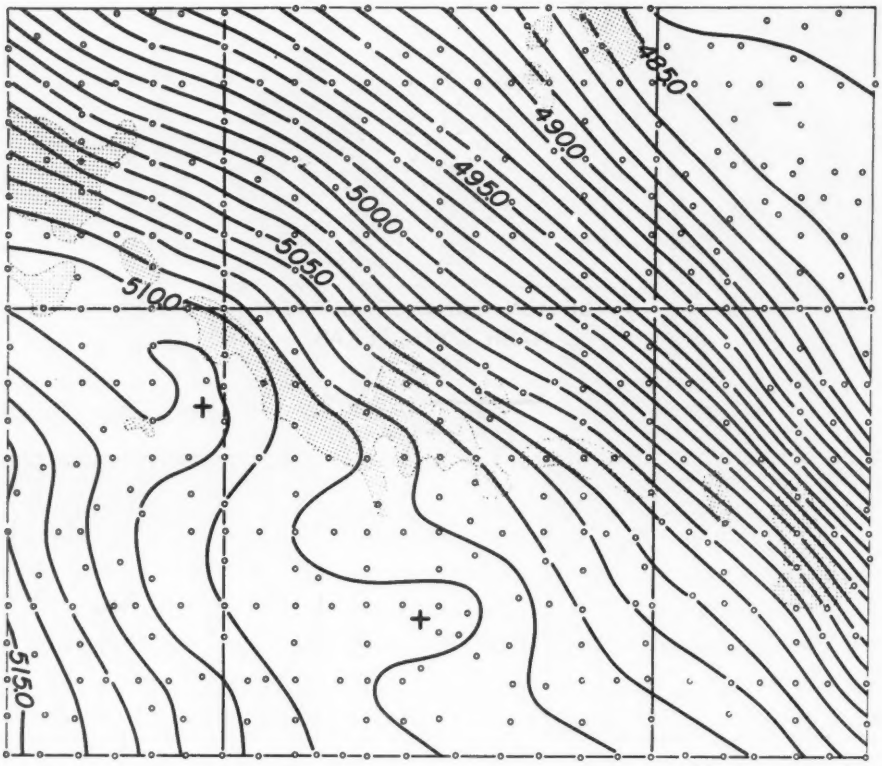


FIG. 3a. Original gravity map made in Southern Oklahoma showing gravity stations and contours. Stippled areas are oil pools.

geophysics (see Figures 4 and 5). World War II diverted its first use to submarine detection. Not until about 1946 was it employed as a commercial exploration instrument.

Magnetic exploration, and especially aerial magnetometer interpretation, are covered in a companion paper by N. C. Steenland (1953).

SEISMIC METHOD

Refraction seismic exploration was begun on a commercial basis in 1923, several years ahead of the reflection method. Contrary to general opinion, however, reflection methods were developed and used in the United States as early as 1921 to map structures in Oklahoma. This pioneer reflection work has been described in a recent historical article by Schriever (1952).

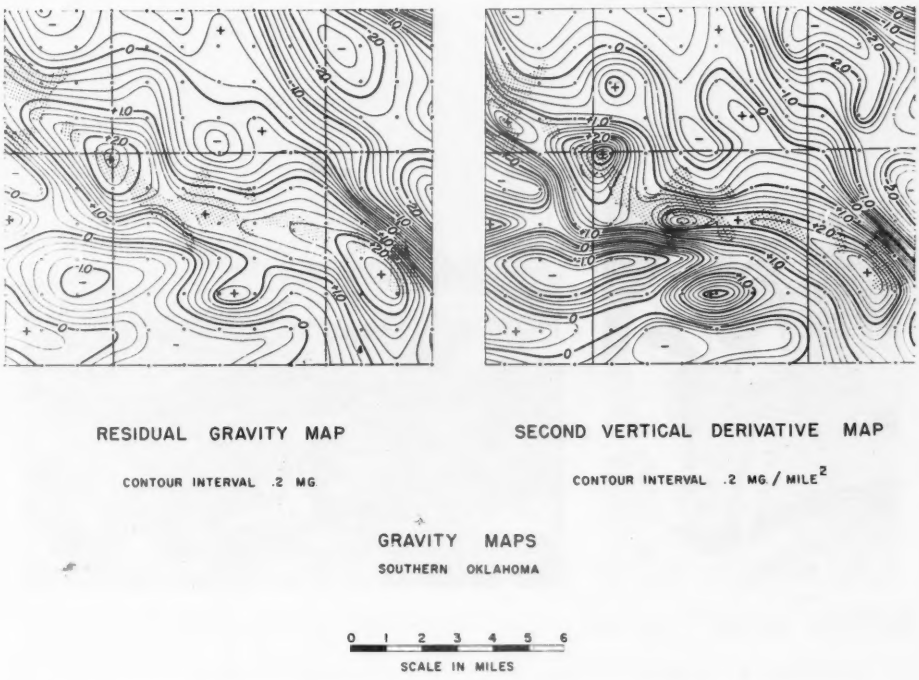


FIG. 3b. Residual and second vertical derivative maps constructed from gravity contours of Figure 3a. Note alignment of maximum trends with axis of oil fields.

The refraction method was almost superseded by the reflection method around 1930, except for specific uses. Current applications of refraction include lowering geophones in a borehole in the center of a shallow or medium-depth salt dome to outline the salt flanks, mapping the subsurface with primary or secondary refractions in hard rock surface areas such as the Edwards Plateau in West Texas; and correcting for near-surface low velocities in conjunction with reflection shooting.

Improvements in reflection instruments since 1940 have resulted in more sensitive, yet sturdier, geophones and recording equipment, which have greater uniformity, and are smaller and lighter in weight (see Figure 6). Thus, we have more accurate and more portable equipment, which is better adapted to extremes of temperature, humidity and atmospheric pressure.

Improved reflection field techniques include multiple patterns of both shot holes and geophones, which are used in an effort to improve directivity and increase the reflection amplitude relative to noise. These patterns often make use of star-shaped or other arrays of shot holes and/or geophones which tend to cancel out extraneous surface or near-surface noise waves. In most cases a larger number of geophones for each trace and an increased number of traces, often 36 or more, are used in difficult reflection areas (see Figure 7). Air shooting is a new

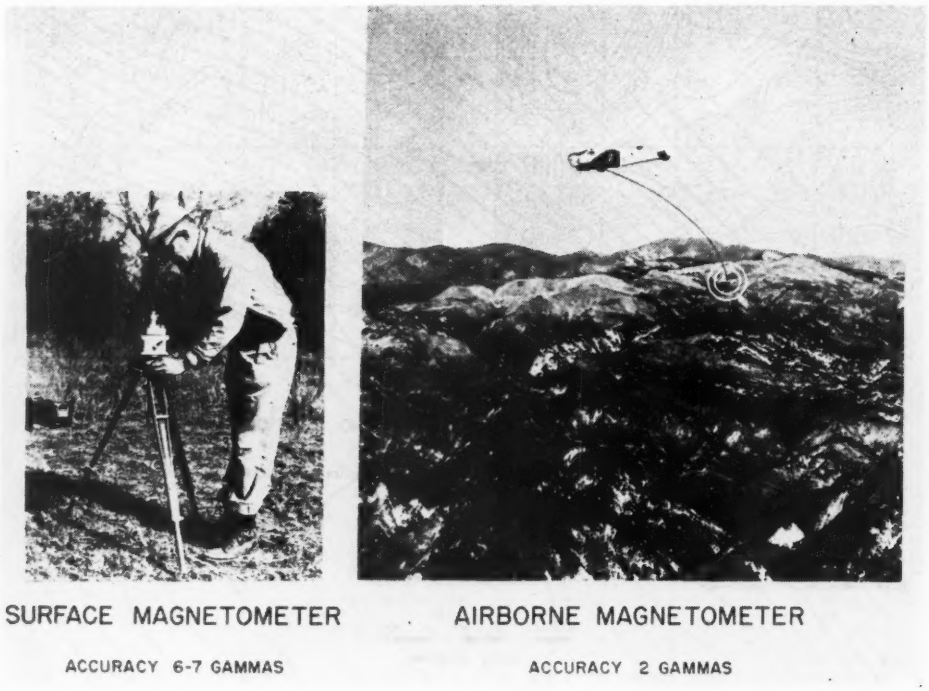


FIG. 4. Comparison of airborne magnetometer and conventional field magnetometer. The airborne instrument is working over an area previously inaccessible for geophysical surveys. Picture of airborne magnetometer through courtesy of Fairchild Aerial Surveys, Inc.

development that is useful in some locations. This has been carried out with patterns of dynamite charges elevated on stakes a few feet above the ground surface, and also with a single charge projected several hundred feet above the ground by a mortar.

Another notable development in reflection field technique introduced since 1940 has been offshore shooting. For this work the equipment and operational procedures have been so greatly improved that seismic prospecting offshore generally can be carried on at a lower unit cost than on land. Among the improvements are the detonation of the dynamite charges suspended within the water and the use of self-pivoting, semi-floating geophones. One method has been developed for both shooting and recording from a single ship that tows a line of hydrophones which pick up the seismic signals while moving through the water.

INTERPRETATION IMPROVEMENTS

Since 1940 many valuable improvements in interpretation have been introduced. Some of these improvements are due to more legible records made by better educated and better trained personnel with more accurate equipment. An increased amount of well velocity data is being used in the same way that paleon-

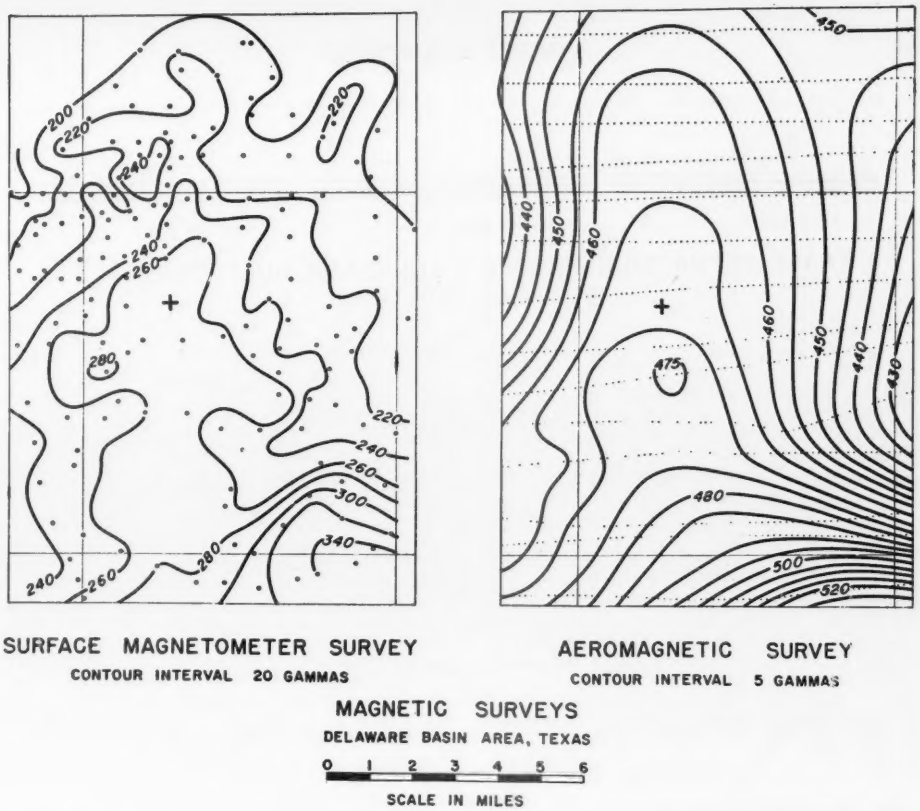


FIG. 5. Comparison of surface magnetometer map and airborne magnetometer map of the same area. Note the relative smoothness of the latter map.

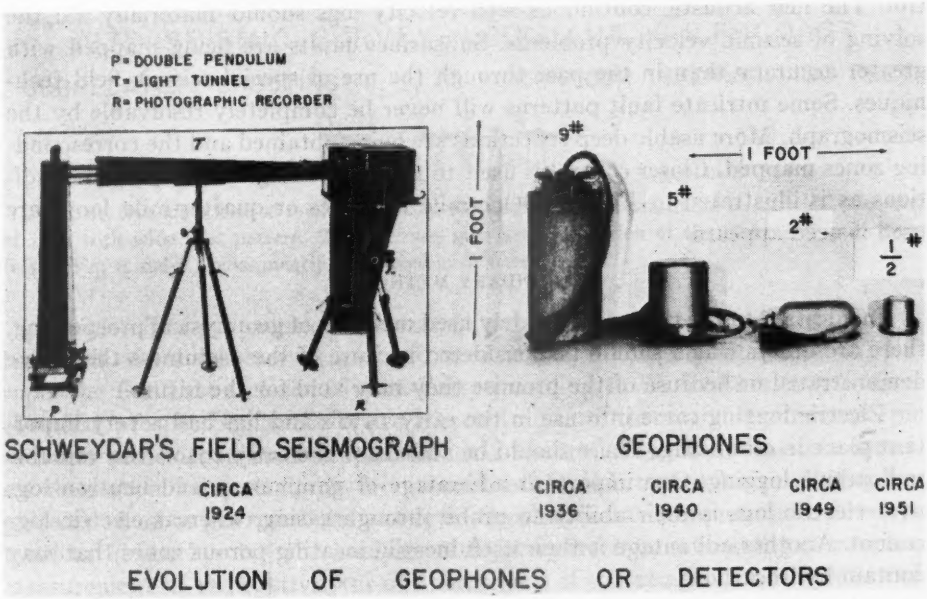


FIG. 6. Comparison of field seismograph detectors over period from 1924 to 1951. The Schweydar instrument was used by the Germans in the first refraction surveys in this country during the early 1920's. Note the steady decrease in the size and weight of the geophones used for reflection work since 1936.

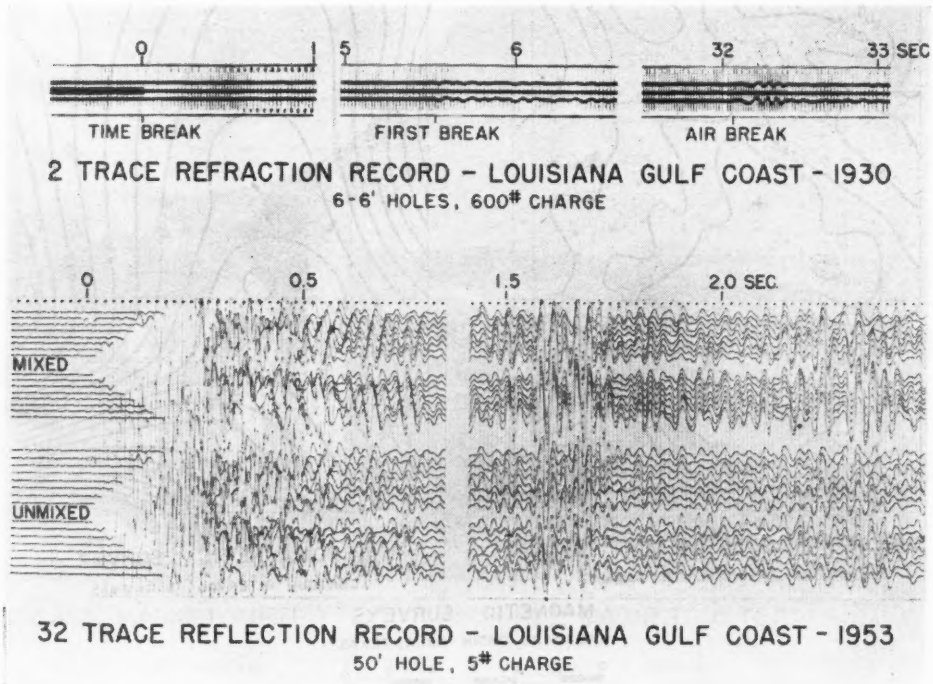


FIG. 7. Comparison of early two-trace refraction record with modern 32-trace reflection record.

tology and electric or radioactive logs are used for both regional and local control. The new acoustic continuous well-velocity logs should materially aid the solving of seismic velocity problems. Subsurface faults are being mapped with greater accuracy than in the past through the use of special seismic field techniques. Some intricate fault patterns will never be completely resolvable by the seismograph. More usable deep reflections are being obtained and the corresponding zones mapped. Closer control is used to good advantage under certain conditions as is illustrated in Figure 8. One-mile traverses or quarter-mile loops are used if need appears.

SECONDARY METHODS

In addition to the three more widely used methods of geophysical prospecting, there are others which should be considered because of the usefulness they have demonstrated or because of the promise they may hold for the future.

Electric logging came into use in the early 1930's and has had a very important place in oil finding. There should be added for the early 1940's the valuable radioactive logging. One important advantage of gamma-ray and neutron logs over electric logs is their ability to probe through casing, whereas electric logs cannot. Another advantage is their usefulness in locating porous zones that may contain hydrocarbons.

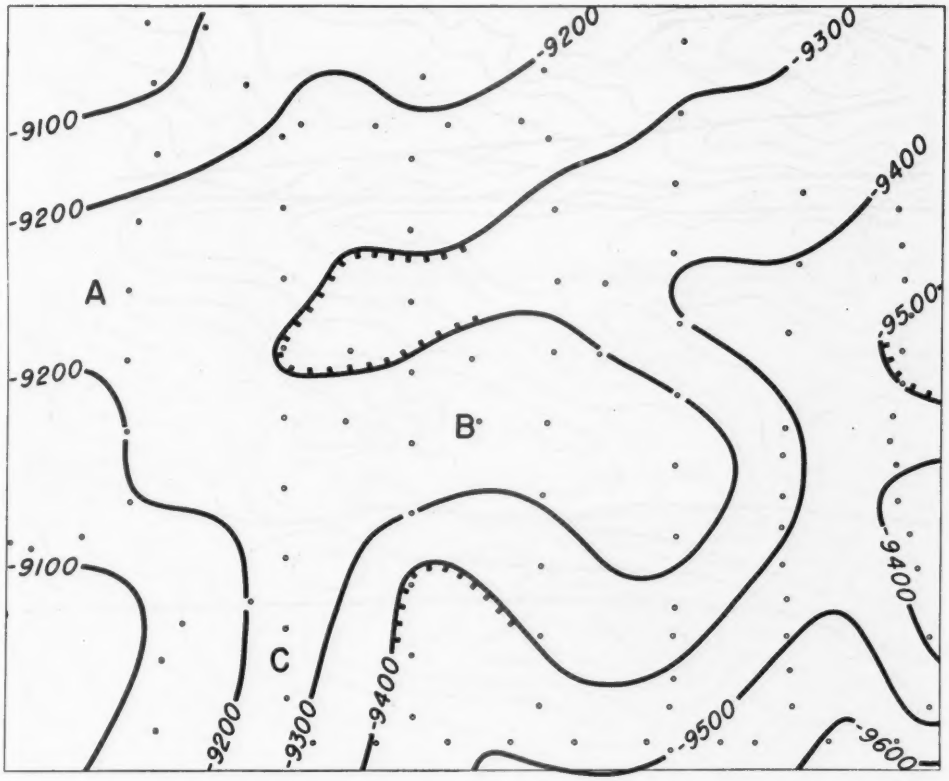


FIG. 8a. Seismic reflection map having contour interval of 100 feet, based on correlation survey of 1935 with wide shot pattern. The contours give little indication of the oil-bearing structures (marked A, B and C) subsequently discovered in this area.

Visible oil or gas seeps on the earth's surface have led to the discovery of at least half of the oil reserves in the United States, South America, Canada, Europe, the Far East and the Middle East, according to W. K. Link (1952). Geochemical prospecting methods are directed toward the search for microscopic seepages rather than macroscopic seepages. Theoretically, then, sensitive chemical tests should detect the hydrocarbons and furnish means for predicting the presence of oil or gas reservoirs at depth. Geochemical techniques under development or in use involve the analysis of light hydrocarbons in soil gas samples, measurement of radioactivity or of fluorescence of soil samples, and detection of

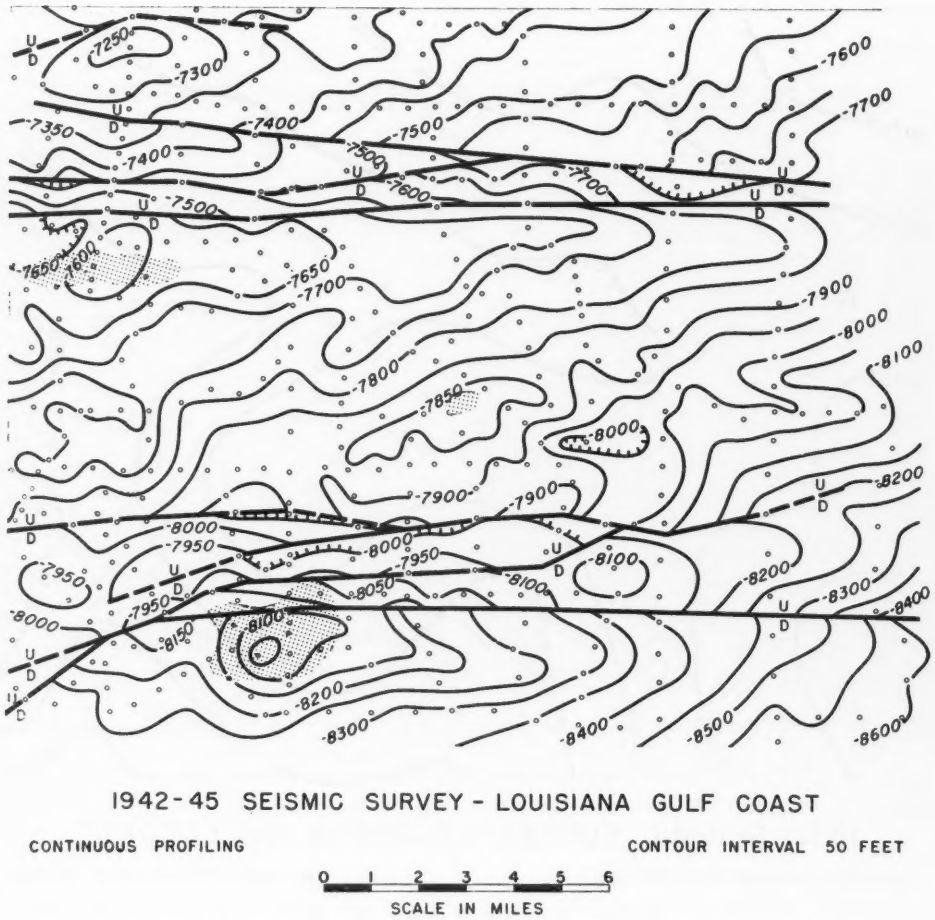


FIG. 8b. Seismic reflection map having 50-foot contour interval based on 1942–45 survey made over area shown in Figure 8a with continuous profiling and closer shot pattern. Note the inclusion of faulting and the oil fields which were discovered as a result of this work.

soil hydrocarbons by counting the population of certain bacteria which are known to feed on hydrocarbon constituents in the soil. A very recent effort is an attempt to measure the surface soil radioactivity with instruments in trucks or airplanes. While a measure of success has been noted from some of the geochemical methods, opinion is divided as to the future of the various forms of geochemical petroleum prospecting.

Electrical methods have been in general more applicable to mining exploration than to petroleum prospecting, but some electrical techniques offer promise. Methods such as electric transients and electric reflections have been under development since 1940 and before. Electric prospecting has demonstrated some usefulness for mapping shallow faults and other near surface anomalies not ob-

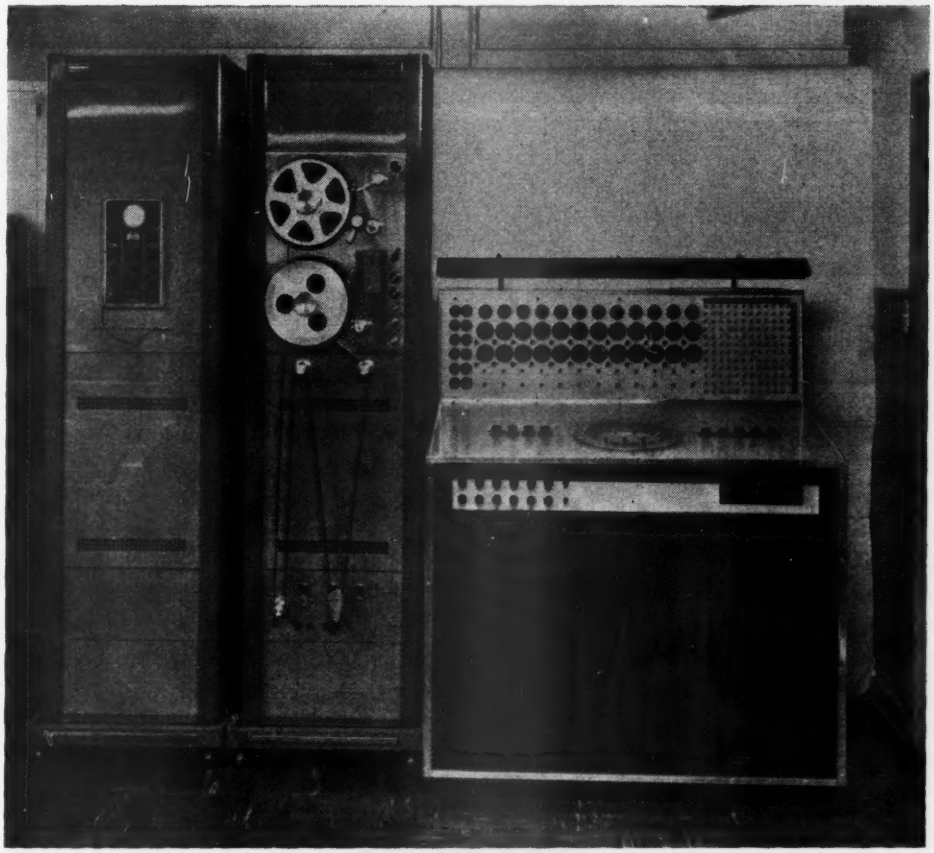


FIG. 9a. Magnetic tape seismic display system. The seismic record is on a 12-channel, 35 mm magnetic tape loop and is driven past a bank of magnetic playback heads at a speed of 15 inches/sec.

servable on the surface. Radio frequency surveys have been introduced as an oil-field prospecting method.

RESEARCH

Research is another type of progress which is of great importance, though its results are not so obvious, nor can it be measured by the standards of reserves or production for the immediate future. Even as research prior to the advent of seismic, gravimetric and magnetic exploration led to the successful initial application of those techniques, so should research further show up in the future in tangible improvements and possibly in new methods. Two types of research are being conducted: fundamental research to improve our understanding of the basic laws and physical processes involved; and applied research or development which has the more immediate objective of direct improvement of geophysical instrumentation and techniques. Until recently, most of the fundamental or long-

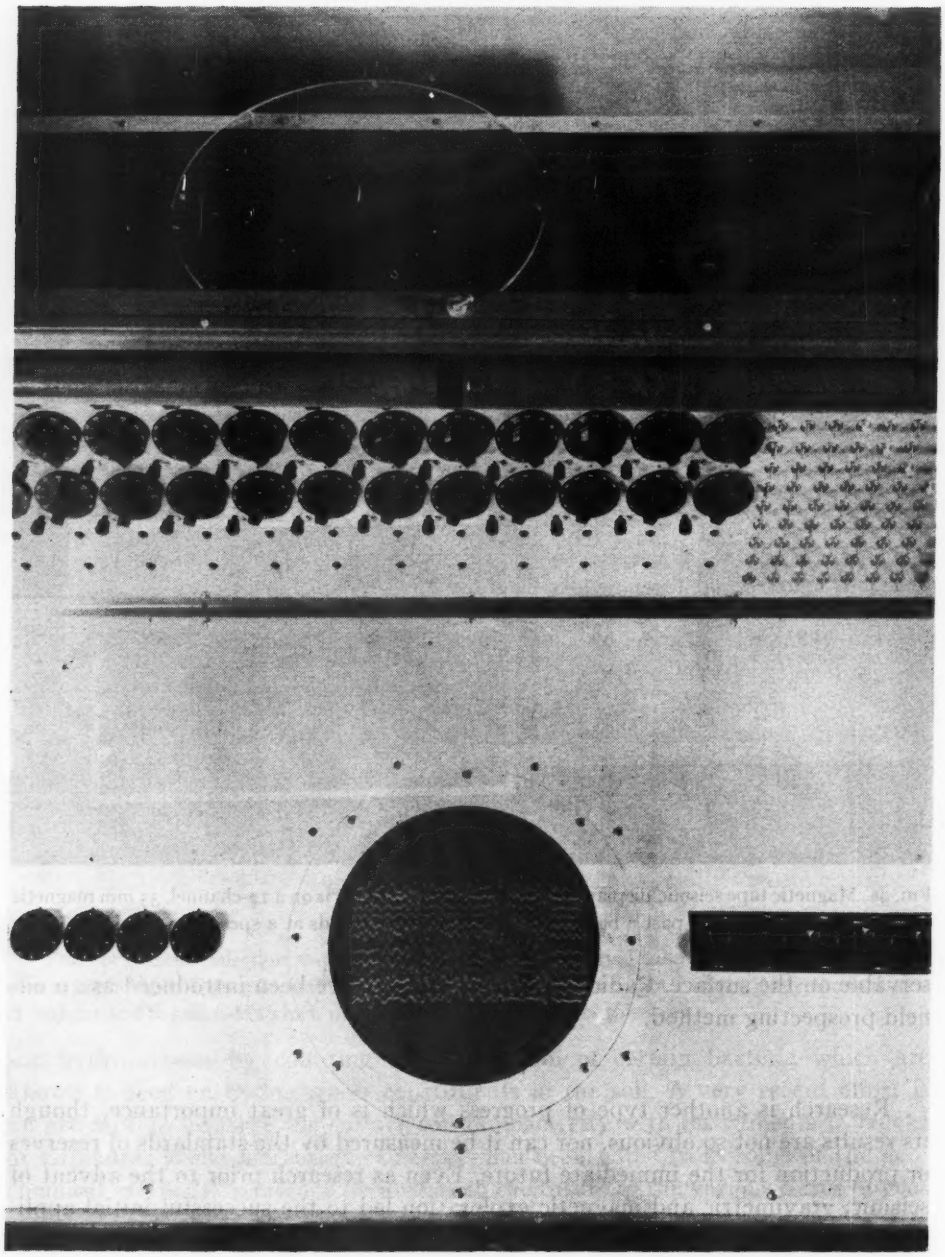


FIG. 9b. Close-up of the cathode-ray screen in the magnetic tape display system. The screen shows a portion of 12-trace seismic record. Filter setting, gain, mix, and time interval displayed are controlled by the knobs and switches and the effect of changes in these settings is observed on the screen.

range research was carried on by universities and endowed scientific institutions. Since the end of World War II, there has been large expansion by the industry in fundamental research on exploration, mainly in the laboratories of the oil companies.

The major part of this activity is related to the seismic art. Despite the wide commercial use of seismic methods, we still need to know a great deal more about the physics of seismic wave propagation. The serious problems presented by N-R, or no-record, areas have led to research in analyzing and identifying the waves making up the "noise" on seismic records.

The revolutionary advances in seismic recording are an example of applied research. At least three systems are now being developed for recording seismic signals on variable area film or magnetic tape for reproduction in the office, with a wide choice of filters, gain levels and mixing combinations. The advantages are great where it is not feasible to shoot more than once or twice in the same hole, or where good results strongly depend on proper choice of filter band. One of the more versatile magnetic tape units places the output of the playback system on a cathode-ray screen after filter and gain adjustments. The seismologist views this screen to guide his choice of filter and gain settings before making his final paper records with a conventional camera. Figure 9 illustrates one such magnetic tape playback and display system.

New methods of analyzing seismic records are being developed. These take advantage of current mathematical analysis techniques and fast computing machines. At present, M. I. T. is organizing, on a cooperative basis, a project to develop computing machinery for identification of reflection signals out of noise background.

In gravity research the principal activity has been in the field of density measurements. A borehole gravity meter is being developed for obtaining subsurface density. Work is going forward on a density logging tool making use of correlation between gamma-ray absorption and density of the subsurface formations.

Fundamental research is being carried on in geochemistry and it is possible that new or more effective techniques may develop.

COORDINATION OF GEOLOGY AND GEOPHYSICS[1]

Prior to the introduction of geophysics in 1922, geology played the only scitific role in the search for oil. Early efforts of geophysicists did not meet with the wholehearted approval of the geological profession. Attempts of geophysicists to resolve a geological problem strictly in terms of physics and mathematics often resulted in a structure or structural trend offensive to geologic thinking. Some competition, rather than co-ordination, resulted.

[1] For an amusing pictorial presentation of some of the ideas in this section, the reader is referred to the set of cartoons on pp. 722–724 of this issue.—*The Editor.*

With time, the number of areas decreased where surface geology could be effectively used. Geophysics was needed where little or no geological control was obtainable. With dry holes on geophysical prospects, the geophysicists realized their fallability. Finally, the necessity for new production and reserves made mandatory a more cooperative effort. In the past few years both geologists and geophysicists have made an effort to learn more about the field of the other. The curricula of our universities and colleges have been redesigned in this direction. More and more, the discovery of oil reserves depends on the complete coordination of the two scientific groups.

CONCLUSIONS

New or more direct oil finding methods may possibly be discovered or perfected. It is more probable, however, that the future of exploration geophysics will be primarily in the continual refinement of the presently known methods.

The cost of geophysical prospecting is much higher than in 1940, partly because of inflation and partly because of the necessity for more detailed work, required mainly because deeper and more complex horizons are now mapped in the areas being explored.

It is probable that more wells per prospect will be needed in the future than in the past for the average discovery. Despite higher costs and greater difficulties, future advances in exploration geophysics and geology, along with teamwork, should assure the United States adequate reserves for a long period into the future.

This optimistic outlook is predicated on our nation maintaining the competitive free enterprise which is responsible for our world leadership in all branches of the oil and related industries.

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A COOPERATIVE PLAN IN STUDENT EDUCATION*

CECIL H. GREEN†

ABSTRACT

Effective exploration is a combination of well designed equipment and competent personnel. The latter factor attains special importance as exploration problems become more complex and competition increases with other industries for scientific manpower. A cooperative plan for undergraduate university students is described wherein aptitudes are measured in a guided course of actual exposure to various phases of petroleum exploration.

The petroleum exploration industry might be concerned over the fact that there still appears no radically new oil finding method just over the horizon or around any next corner. Instead of worrying unduly, however, the industry prefers to concentrate on the continued opportunity for discovering new petroleum with existing methods. In doing this, it recognizes the existence of three frontiers.

Perhaps the most obvious of these three frontiers comprises those remaining territories which have received incomplete attention to date. Thus domestically we can indicate parts of the North Central Plains, of the intermountain region of the Western States, and, of course, much of the offshore area along the Continental Shelf. Then in Canada there is the extensive bush country from Peace River to Upper MacKenzie River basins. Obviously, this particular frontier of unworked regions does not account for the continued large-scale geophysical operations throughout long established oil provinces, such as in the Southern Mid-Continent and in California. There, year after year, we witness the application of geophysical effort by orthodox methods. For example, in the region comprised of Texas and Louisiana alone—where it would indeed be difficult to find an area not previously shot over, probably several times—we see some 300 seismic crews, or about 38% of the total world effort.

This persistent seismic activity in old territory represents the second exploration frontier. Here the seismic effort is well guided for each prospect by a process of adjusting instrumentation and subsequent interpretation for the purpose of proving, or disproving, a previously adopted geologic premise. California provides some excellent examples of this process of working from a likely hypothesis to a logical conclusion. Thus, for California, it might have been said, as far back as before World War II, that further oil discoveries of any consequence were unlikely. However, discoveries in the Cuyama Valley, the Sacramento Valley and at Castaic Junction not only gave this so-called mature province a new lease on life but inspired fresh instrumental approaches by the seismologist. Alberta, Canada presents another very good example. Before the advent of Leduc in February, 1947, there were less than a dozen seismic parties searching, without worth-while

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results, for structural folding in widely scattered areas through the southern part of Alberta. However, when the discovery of oil at Leduc indicated that Devonian reefs were the prime reservoir objectives, then the seismic strategy was not only adjusted immediately but its effort expanded by an enthusiastic industry to its present phenomenal level of around 160 parties throughout the four western provinces. To a large extent, work on this second exploration frontier involves the joint efforts of the geologist and the geophysicist, with the value of results proportional to the degree of integration existing between them.

There remains a third frontier, comprising areas commonly considered unworkable. We are all aware of certain localities, as well as broad areas, which are rated highly in petroleum possibilities, and yet which have defied repeated seismic attacks. In some instances, the sub-surface geologic configuration is overly complicated through extreme folding as well as faulting. Then perhaps the sub-surface beds are not competent enough to be resolved into reflection horizons. In other circumstances, the difficulty might exist at or near the surface, where certain rock materials cause either undue absorption or scattering of seismic energy. This is thought to be the situation in the Edwards Plateau Country, the Delaware Basin, and in parts of Florida. In these areas the difficulty is characterized by an undue ratio of noise to signal strength. In some instances the frontier in these areas is being pushed back somewhat by experiments with instrumentation—particularly by use of multiple seismometers, pattern shots, or combinations of the two.

Another problem on this third frontier which is gaining increasing recognition is the existence of multiple reflections, especially in offshore shooting.

Summing up for the exploration seismologist, it is quite apparent that he is engaged in an art as well as a science. While instrument performance is important, the ingredient of the human factor is far more essential, and is becoming increasingly so, as problems encountered on the second and third frontiers become still more obvious.

Thus, people become more than ever the prime asset in a seismic surveying program. The degree of success, in terms of accuracy and completeness, is proportional to, and no better than, the integrated effect of such individual attributes as native ability, initiative, imagination and experience. I refer to the kind of effort which is applied all along the line, from the initial procurement and processing of the raw seismic data to the subsequent interpretation and coordination in some central office. Incidentally, I believe the mistake is committed on occasion of placing principal emphasis on the latter function (that is, on delayed interpretation and coordination), when, as a matter of fact, the application of top intelligence and experience in the experimental manipulation of the instruments is equally important. I refer to the basic idea that the outcome of a seismic survey can be no better than the quality of the raw data or the skill applied during the actual survey toward correlating unexpected events on the reflection records with observed geologic circumstances. Thinking on instrumentation had better be kept

flexible since the man who is taking the first interpretive look at the records has logically the best opportunity to administer the adjustments. Thus, ideally, the Party Chief-Seismologist should be of such caliber as to be able to translate the stated geologic problem into the best seismic picture.

In specifying the importance of the human factor in the over-all seismic effort, it might be well to review the natural personal makeup of a potentially good exploration geophysicist. I have mentioned already such mental attributes as native ability, initiative and imagination. In order for such a man to have his head up in the clouds of theoretical knowledge and yet have his feet planted on the terra firma of good common sense, he should be sought among university engineering and science graduates. Here we encounter a two-fold difficulty. First, there is the prevailing competition for the insufficient output of engineering graduates, not only between like companies, but between industries (including Civil Service). Second, there is the influence, or rather scarcity, of still another vital attribute—positive interest, or the necessity for the individual to prefer exploration geophysics to the exclusion of any other endeavor, so that in dwelling upon its interesting facets he is relatively unmindful of its shortcomings. The old saying, "You can lead a horse to water but you can't make him drink" is quite applicable. Self-generated inspiration and enthusiasm are wonderful catalysts when it comes to squeezing useful information out of marginal quality seismic data—a customary hiding place of remaining domestic oil fields in old areas.

The fact that the exploration industry has increasing need for competent men with natural bent, especially in the face of the existing short supply, merits plenty of positive action. Without question, we should continue to move in the direction of developing closer ties between industry and education. Around the country, how many high school seniors, or even university students most of the way through science and engineering courses, possess much knowledge of the various avenues of endeavor within the petroleum industry? I venture that there is no large percentage, with still fewer having any specific notion as to the nature of exploration geophysics. The S.E.G., through three Committees—i.e., Public Relations, Education and Student Essays—is attacking the problem already on a broad front.

Industry, in turn, has taken a positive step to correct the situation through inducing young men to enter the exploration industry by offering financial aid in the form of scholarships—but mainly in geology rather than geophysics. This is a commendable expression of interest and should, of course, be continued, for, without question, there will always be potentially good men who would be lost to the industry without such financial assistance.

However, there seems to be a need for supplementing the scholarship arrangement with a more intimate relationship which would involve all three elements, i.e., students, teaching faculty, and industry. On the basis that teamwork —integrated effort again—accomplishes more than individual play, an experiment was evolved in 1950 between the Department of Geology and Geophysics

at the Massachusetts Institute of Technology and Geophysical Service Inc. to test the effect of bridging the gaps between the students, teaching staff and industry through working together in a Cooperative Plan.

Very briefly, the Cooperative Plan comprises a formal arrangement for assigning students to GSI for work on its various domestic seismic parties during the summer vacation period following their Junior year. The purpose of this summer work session is to provide students with a complete exposure to the seismic exploration profession by rotating them through the complete range of helper positions—not only in the field operations proper, but in the party office as well. It is important that the students learn the various job routines by actually doing, rather than just watching, so they are given the responsibility for providing vacation relief for permanent GSI workers. In this manner, the students are afforded excellent opportunities to test their natural skills in each phase of crew activities, and at the same time to acquire a strong appreciation for the great importance of teamwork in turning out a good quality end product—i.e., subsurface information.

The MIT students will have spent the previous summer in a field geology camp administered by the MIT Department of Geology and Geophysics at Antigonish, Nova Scotia. Therefore, upon completing the summer assignment with GSI they will have had a broad look at exploration in action and, in consequence, will have developed automatically an improved sense of direction in their projected life work. At least, they are then in a better position to exercise more mature judgment in charting final courses of study, either more strongly toward geophysics or away from it, as their own convictions then dictate.

The Massachusetts Institute of Technology is considered the key school in the Plan because Professor Robert R. Schrock, head of its Department of Geology and Geophysics, is co-author of the Plan and is supported by an enthusiastic faculty, including Professor Patrick M. Hurley. Moreover, it has been deemed important to take advantage of interest from other universities in order to provide a sufficiently large aggregate of selected students for the course. Thus, to date we now have the cooperative support of Professor John C. Hollister, head of the Department of Geophysics at the Colorado School of Mines, as well as its Dr. George T. Merideth; also Professor Wilson M. Laird at the University of North Dakota and Professor L. R. Wilson at the University of Massachusetts—all of whom sent undergraduate students to the Plan a year ago and are expected to repeat next season.

The Cooperative Plan would not be a good venture unless it were amenable to evolution. For instance, it was realized that the students should be given some formal preparation in advance of their actual field assignments, so that minimum time would be lost in the process of adjusting to strange surroundings and new associates. To further orient the students and to insure their working during the summer with best possible purpose, it was felt that they should be apprised of the importance of geophysical exploration plus its position in the over-all com-

position of the petroleum industry. So, an orientation session in Dallas was adopted as a worth-while feature at the opening of the summer session. Representatives of the teaching staffs have been on hand to audit these sessions.

Starting as a three-day affair, the orientation session merits expansion in the future to a full week in order to provide sufficiently broad treatment. While the staffs of GSI and Texas Instruments Incorporated, its affiliated manufacturing company, can appropriately present information on matters within their own operations, it is logical, and therefore preferable, for others to describe the circumstances surrounding the use of the seismic method and to portray the position of geophysics and exploration in the organization of the petroleum industry. As a matter of fact, the composition of the orientation program itself provides an excellent example of cooperative effort, for in addition to the efforts of GSI and TII, valuable contributions have been made in the past by key staff members in Dallas of several major petroleum organizations.

The resultant wide range of subject material provides an insight into many phases of the petroleum industry, all of which have at least indirect influence upon the conduct and use of geophysical exploration. The last Dallas orientation conference comprised:

1. Geophysical Service Inc.—Presentation of the fundamentals of seismic prospecting, the principal specifications of equipment, and the organization of personnel.
2. Texas Instruments Incorporated.—Portrayal of the nature and scope of research and engineering aspects, the composition and varied functions involved in this integrated development and manufacturing organization specializing in electro-mechanical apparatus.
3. The Atlantic Refining Company.—A varied program presenting some legal and economic aspects of the petroleum exploration industry, a comparison of the reflection seismograph with other echo methods; background experience of typical key men in an exploration organization, a tour of the Atlantic Research Laboratories.
4. DeGolyer and MacNaughton.—Presentation of economic and engineering aspects of reservoir evaluation, discussion of the interrelation of various geophysical methods in the light of geologic needs, a case history treatment of some developments in the Wilcox Trend in Central Louisiana.
5. Magnolia Petroleum Company.—A portrayal of the organization and operation of an exploration division within an integrated oil company, the organization and scope of research and development projects within its laboratories, an inspection tour of the Magnolia Field Research Laboratories.
6. Seaboard Oil Company.—Presentation of geophysical-geological case histories of several recently found West Texas fields, demonstrating the value of learning through good examples.
7. Standard Oil Company of Texas.—The design of a representative explor-

ation program and the part played by the seismograph.

8. Sun Oil Company.—The nature of statistics in petroleum exploration; answers to the pertinent question, "What does the exploration industry expect of the seismograph?"

It might be considered that the cooperative idea finds special encouragement in Dallas and that a real check on its merit might well consist in trying it elsewhere. So largely through the material interest and support of Professor J. Tuzo Wilson, of the Department of Geophysics at the University of Toronto, and again with the direct help of the petroleum companies, a similar plan was launched last year in Western Canada. The orientation session, held in Calgary, featured the presentation of the same wide range of information on the industry as a whole by staff men of Amerada Petroleum Corporation, Anglo-Canadian Oil Company, The California Standard Company, Gulf Research & Development Company, Hudson's Bay Oil and Gas Company, Imperial Oil Company, Ltd., The Ohio Oil Company, and Socony-Vacuum Exploration Company.

Having been briefed in the orientation session, the cooperative student is now prepared to derive a maximum amount of mental benefit, in addition to the nominal sum of money he may save from his wages. However, to provide a psychological urge to use his faculties at all time—that is, to force interest through observation and discussion—he is forewarned that at the end of the season he will be expected to prepare a report on any topic relating to the work. Since there are no commitments on either side regarding future employment, the student is quite at liberty to express his opinions. Copies of his final report are submitted to GSI and the universities. GSI takes it upon itself to grade the student, not only on these final reports, but in the light of bi-weekly Party Chief reports, examined and signed by the student, wherein he is rated in terms of common sense, degree of interest, aptitude, and ability to get along with others.

One might ask: What has the Plan accomplished, especially in terms of selling desirable young men on exploration geophysics. Quite frankly we do not know yet, since the Plan must be considered a long-range one. On the other hand, we are sure that it is far from altruistic since already we recognize valuable short-term benefits.

First, from the standpoint of education, the Plan has evidently demonstrated merit, since MIT has decided henceforth to award academic credits to its students who participate satisfactorily in the Plan.

Next, from the viewpoint of the student, the orientation session affords an opportunity to listen to a variety of key men in the industry, whose donation of time to the cause of enlightenment does not go unappreciated by the students. It is to be expected that the average advanced student unconsciously acquires some exalted ideas regarding his apparent importance as he notes competition among company personnel representatives for his permanent services. In the words of a Toronto student who gave voluntary expression at the end of the

Calgary session last season: "I felt very cocky at the beginning of the orientation session but now at the end of it I feel downright humble." Such healthy conditioning of mind through acquisition of proper perspective toward our field of endeavor could be ample reward in itself for the trouble and expense involved in the orientation session. The student is further impressed at the outset with the surprisingly large array of factors—economic as well as technical—which affect exploration. He learns that equal opportunities lie in both geology and geophysics and that exploration, to be truly effective, requires a blending of the two.

Finally, the permanent staff members of GSI benefit also from the Plan. I refer to its inspirational value for the Party Chiefs in particular, who, when called upon to explain procedures and to answer the questions of these bright-eyed young men, occasionally find it necessary to brush up on their own understanding and to formalize their thinking. The worst thing that can happen to an exploration organization is the encroachment of staleness, or routine thinking. Without question the Cooperative Plan contributes materially to keeping us alert and out of the rut of complacency.

A SAFETY PROGRAM—MANAGEMENT'S RESPONSIBILITY*

G. H. WESTBY†

ABSTRACT

The extremely poor safety record of the contract geophysical industry should be corrected not only for the humanitarian and economic gains it would bring the individual company, but also for the improvement it would make in the industry's public relations and ability to attract technically trained men. Management of the geophysical contracting companies should be cognizant of the importance of such a program and eager to participate in the S.E.G. safety program. Management of the oil companies, represented by those who are responsible for hiring contract geophysical companies, should help assure the success of this program and its related good consequences to the oil industry by demanding that geophysical contracting companies, in addition to meeting all their other requirements, have a safety program and cooperate with the S.E.G. in its safety program.

This is not to be a paper on a safety program replete with statistics. Management—as noted in the title of this paper—does not primarily mean the management of geophysical contracting companies. The management to which this paper is chiefly directed is represented by the head of an oil company exploration department, the chief geologist, or the chief geophysicist who selects the contract geophysical crews which are to work for them.

In this article it is my intention to outline the extremely poor safety record of the geophysical contracting industry as a whole, to point out how a better safety record would improve the public relations between the oil industry and the public (particularly the exploration industry and the public), and to show how it would improve the efficiency and economy of operation of geophysical crews.

It is also my desire to suggest that the men on the policy-making or seismic crew hiring level in the oil companies are in an excellent position to cure this illness and to secure from a cured patient considerable benefits for their own oil companies and for the oil industry in general. The way some of the geophysical contractors and drilling contractors regard public relations and safety reminds me of an efficiency apartment skit staged by the great comedian Bert Williams in the Ziegfeld Follies years ago. In this skit Bert showed his straight man over an efficiency apartment. He pushed a button and a bed slid out of the wall. He opened folding doors that concealed a Pullman kitchenette and other trick gadgets. Finally, duly impressed, the straight man asked, "Bert, what do you do do about the garbage?" "Why, that's easy," Williams replied, "We just kicks it around until it gets lost." Present and past experience has shown us that you just can't kick safety and public relations around until they get lost.

The Society of Exploration Geophysicists has recognized the great importance of these two factors in our industry and has created committees to work

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toward improving each. A fine start has been made by both committees, but each needs your help, as management, to achieve the desired results.

Mr. Bart W. Sorge, in his excellent paper, "Safety Is Our Responsibility," states that the contract geophysical group has an accident frequency which is five times as great as that of the petroleum industry as a whole. It has a severity rate which is almost twice as bad as the petroleum industry's. If we may consider that the geophysical contracting companies cooperating with the Safety Committee of the S.E.G. have safety programs and the others do not, we find that all of the larger contracting companies (that is, those with forty crews or over) are cooperating; approximately half of the medium-sized companies (those operating between fifteen and forty crews) are cooperating; and only six out of approximately sixty-five other geophysical contractors, operating less than fifteen crews, show any participation in the efforts of the S.E.G. committee. There may be some, however, who do have safety programs who are not cooperating with the committee's efforts.

Since the record of the contracting industry has been determined from those companies cooperating with the committee, it is reasonable to suppose that the companies not reporting to the S.E.G. Safety Committee had an experience as bad or worse than those who have commenced safety programs.

As far as safety is concerned, it is evident that the shot hole drilling contractors are in a category all by themselves. At least five employees of drilling contractors have been killed within the last few months. If such statistics were included in the foregoing, the comparison between the contracting industry and the oil industry in general would be unbelievably bad.

Again may I emphasize that I am discussing the problem of the safety program for the geophysical contracting companies and not for the geophysical crews run by the oil companies themselves. It is very apparent that the oil companies have been safety conscious for many years and have excellent safety programs which are closely followed and well administered.

Why do oil companies and most other large industrial organizations have safety programs? There are two logical bases for an active managerial interest in safe working procedures—humanitarian and economic. The humanitarian has long been recognized, but relatively little was done about it until it was pointed out that in addition to being the socially and morally correct thing to do, it also paid off in dollars and cents.

The unfortunate victim of an accident suffers not only physical pain and reduced earning power, with the resultant lowering of the standard of living for himself and his dependents, but also a lowered morale, which is even worse than either of the other two. The lowering of morale not only affects the individual worker and his family but also his associates in the work place.

As early as 1908, Judge Gary, then Chairman of the Board of United States Steel Corporation, said, "We should like to take a prominent part, a leading part, in any movement and in every movement that is calculated to protect the

employees of the different corporations in which we are interested, and any requisition which is made for the expenditure of money to install equipment to protect our people will be honored." Charles R. Hook, while president of The American Rolling Mill Company, once said, "You may be interested to know that in almost every meeting of the Board of Directors the company accident report is read and explained by the vice president and general manager. The Board members recognize that the accident report is an important barometer of organization effectiveness, and if this index is not where it should be, then general management had better get busy."

There were other compelling facts which urged Judge Gary to place into operation a strong safety program. For example, back in 1907, in one of the popular magazines of the day, appeared a headline, "Making Steel and Killing Men." It recited that 46 men were killed in one plant that year and that the "United States Steel Corporation, in the person of the Illinois Steel Company, was censured six times last year by coroners' juries." Aside from the cost, it was obvious that the public clamor aroused by such headlines could be exceedingly detrimental to the general steel industry and might induce handicapping regulations, as well as difficulty in enlisting further workers at reasonable wages.

It is noteworthy that the program installed by Judge Gary and continued, with improvements, since that time has moved the steel industry into one of the lowest accident-frequency rate groups in all industry. Considering the heavy type of activity in the steel industry, this achievement is remarkable. You will note, by listening to your United States Steel hour once a week, that this program is still continuing.

As two other examples of extremely bad safety records which have been converted into excellent records, let me cite two in the general oil industry.

Several years ago a certain large oil-well servicing company, operating a large fleet of trucks, found that it could not buy insurance at any price. It was not a question of cost, but the company's experience over a period of years proved that no insurance company could take the risk *at any rate*. The management, in facing this problem, started a well-managed and supported safety program, and today they not only have insurance but buy it at a substantial experience credit.

Another of the outstanding examples in accident prevention is that of a large oil company with its head office in Tulsa. It started an accident control program in 1926. In that year its frequency rate was 87.9. By 1932 that rate was down to 18.9. By 1952 it was down to 2.9, which is one of the lowest in the industry.

If you are wondering how this frequency rate is determined, it means the number of lost-time accidents per one million man-hours worked.

Has accident prevention paid this company? The 1952 frequency of 2.9 means 58 lost-time accidents in 1952. Suppose they had had the 1932 frequency of 18.9; instead of 58 they would have had 378 lost-time accidents. Accident control has certainly paid off.

Experience shows that the average industrial accident will cost the employer five dollars for every one dollar of direct cost. We believe this figure is conservative. Accidents cost money. If you buy insurance to cover part of the loss caused by these accidents, then they cost money in another way. In effect, they determine the cost of the insurance you buy. Public liability, auto liability, workmen's compensation, and equipment insurance are all affected by loss experience. Our insurance carrier reports to us that the rates of the Manual for Standard Rates for Workmen's Compensation are set by the National Council for Compensation Insurance. These standard rates reflect the industry experience for each occupation and each state. The manual is then adjusted annually for the actual experience of the insured company. The company may have a 10, 20, 30 percent or higher credit. I am told that one oil company in Oklahoma has a 70 percent credit. Our company is operating with a credit of more than 20 percent this year. You may also have a debit, or increase, in your standard rates.

It is easy to see that if a company pays $50,000 a year for compensation insurance at these standard rates, the difference between a 10 percent credit and a 10 percent debit is $10,000. It is, therefore, worth exactly $10,000 for such a company with such a 10 percent debit to prevent enough employee accidents to gain instead a 10 percent credit. These debit and credit ratings are used by most insurance companies as a basis for all kinds of compensation insurance that they sell.

Accidents, then, seem to be tremendously expensive in direct insurance cost, in direct and indirect additional operating cost, and in personal pain, suffering, and hardship to the injured employee.

We have pointed out earlier that a strong accident control program, carried on through the supervisory personnel, supported by management, can reduce accidents and eliminate these wastage factors of manpower, money, and work time.

Now, let's get back to our own industry of geophysical prospecting. In the late twenties and early thirties, with only a fraction of the seismograph crews in operation that are now in the field, a serious explosive accident, involving the killing or maiming of several men, was a tragically frequent occurrence. Not only were employees of oil companies and contracting companies killed and maimed, but, in several instances known to me, local farmers, workers, and innocent bystanders were killed. If this frequency and severity rate of dynamite accidents had continued with the great acceleration of geophysical prospecting, it is quite probable that the great public clamor aroused would have resulted in restrictive legislation which would have hindered exploration for crude oil by this method so drastically that not only would there be little geophysical business, but there would have been much less oil discovered and produced. Fortunately, legislation was utilized which was not restrictive but safeguarding, and by an excellent program administered by the Bureau of Mines, all companies were brought into line to respect the regulations governing the handling and trans-

portation of explosives. This safety program was so successful that this hazard has been almost eliminated, so that today it is almost non-existent as an accident factor in the geophysical industry. Do we need a better example than this to show that accidents can be prevented and that a proper safety program, set up with reasonable and sound safety rules and regulations, can achieve the desired results?

The top councils of the Society of Exploration Geophysicists have wisely determined that there are three major problems confronting the geophysical industry today which must be solved for our continued growth, public acceptance, and efficiency. These are: A safety program for all geophysical contractors; a public relations program for the geophysical industry; and a recruiting program for men to become interested in our industry as employees. To my mind, these three are very closely tied together, with the safety program having a controlling effect upon the other two.

Not many years ago a poll taken of American public opinion concerning the oil industry revealed to the leaders of our industry the dismaying information that the American public did not know the facts concerning our industry and were inclined to regard it unfavorably, as monopolistic, as embodying the so-called evils of big business, and as fair game for restrictive and punitive legislation as well as higher taxes. The result of that poll influenced the American Petroleum Institute to embark upon a campaign of public relations to tell the American people the facts about the oil industry. That program is being continued today by the Oil Industry Information Committee, with ever-growing effectiveness. There is no need to "sell" to the petroleum industry the advantages of a good public relations program or a safety program. The industry as a whole has embarked upon well-directed campaigns in both of these important fields.

Proper safety and public relations programs for all companies, large and small, of the geophysical contracting industry are a vital necessity. These contracting companies are a growing part of the oil industry, are recognized by farmers, ranchers, and land owners as an integral part of the industry, and must, therefore, adhere to the standards of safety and efforts toward good public relations set by the oil industry. Since they are usually the vanguard of oil operations and, therefore, provide the first contact of the operating end of the industry with land owners and ranchers, it is of paramount importance that this first contact be favorable. If favorable, the way is smoothed for later seismic crews and for lease and production men. If unfavorable, exploration permits become high priced or unavailable, local restrictive legislation may be enacted, and certain companies may even be refused desired leases.

A crew which has management that emphasizes and supports a well-administered safety program will be a careful, efficient, smoothly running organization that achieves good production with no lost motion. A crew without a safety program tends to endeavor to secure a good production record by rushing about, taking careless short cuts in operating procedures, antagonizing the farmers and

local officials by cutting and leaving down fences, leaving used shot holes unplugged, unnecessarily cutting up fields and roads, and perhaps driving heavy trucks fast and carelessly enough to endanger local traffic or scare the farmer's daughter. The lack of a safety program not only costs somebody money, but it is a sure way to create bad public relations for the oil industry.

Having no safety program may affect the ability to hire men. Certainly potential employees may shy away from occupations which are hazardous. Our company finds that a new employee in the field has about a fifty-fifty chance of being injured within the first three months of his employment, despite our safety program. Obviously, we must concentrate on this part of our program. With no safety program whatsoever, it would seem that the new employee could hardly escape an accident in the first three months. If drillers' helpers on contract drills are killed at the rate of five in two months, we may find it difficult, if not very expensive, to keep such positions occupied. Since a training program on a crew for university graduates usually involves working for a period on each unit of the crew, we must make such occupation safer or lose good technical men by accident or desire to seek other employment.

Let us sum up the reasons for insisting on a strong safety program on geophysical contract crews and examine the impelling motives which might enlist your active and compelling support.

First is the economic benefit. This is a direct benefit to the contract crew organization, but only an indirect benefit to the oil company client. I can hardly believe that the cost savings from a safety program could be passed along to the oil company client in lower contract prices. The fact is that the contract price of seismic crews is one of the greatest bargains in the oil industry today. Comparing contract prices and costs of the contract in 1939 with those of 1952, we find that for the same number of men the salary costs have doubled, for the same number of units of equipment, the costs have trebled, but the price the contractor charges has only been increased by one-half. There is no other service or commodity in use or sold by the oil industry which shows such a small increase over the 1939 price. The price of 40-gravity oil has more than doubled since 1939. However, to provide proper men and service, the contractor must be making a profit. A safety program might increase his profit margin and thereby benefit the client in better men, better equipment, and better facilities provided.

It may seem out of place to discuss prices before this technical body, but much as we may say we are following only scientific pursuits, we can pursue this happy vocation simply because and only as long as it means dollars in the pockets of the owners of each company. As a good client of ours once remarked, "You may say your objective is to render a top scientific service, but your real objective is to make money—as is ours." It doesn't hurt now and then to recognize our basic motives.

The humanitarian motive of alleviation of suffering of the injured employee and the resultant lowering of morale and hardship on his family by elimination

of accidents through a safety program is certainly present in the minds of the direct managers of the contract organizations, and it may be in the thoughts of the client hiring the crews, but the effect on the client is as indirect and distant as the living conditions of the natives of the Belgian Congo.

The effect on the future manpower of the exploration industry by virtue of the presence or absence of a good safety program cannot be easily or concretely analyzed. We must admit, however, that from experience in other industries, the effect is real. We can be certain that if headlines reading "Oil Search Kills Men" were prevalent today, as they were from the explosive accidents years ago, the recruitment of employees would be more difficult and expensive.

The real compelling motive for clients to demand a safety program on their contract crews is the effect on the public relations program of the oil industry. Do you want restrictive legislation covering seismic work on government lands? Do you want high permit costs or local or state restrictive and sometimes crippling legislation? Do you want embittered farmers, land owners, and local law officials as a group to work with for permits, leases, or other development negotiations? I am certain you do not.

Now, what is the simple cure I mentioned earlier in this paper? You control the hiring of seismic crews. You ask for certain equipment, personnel, or methods that you require, and you choose the contractor best able to fulfill your desires at the proper price. If you really want a safety program in the contracting industry, hire only seismic contractors who, after fulfilling all your other requirements, will answer "yes" to both of the following questions:

1. Do you have a safety program?
2. Are you cooperating with the Safety Committee of the Society of Exploration Geophysicists?

It is as simple as that.

DETECTION OF REFLECTIONS ON SEISMIC RECORDS BY LINEAR OPERATORS*

G. P. WADSWORTH,† E. A. ROBINSON,‡ J. G. BRYAN,§ AND P. M. HURLEY‖

ABSTRACT

Linear operators are used as a statistical tool in the analysis of seismic records. It was found that when an operator is chosen for a non-reflection interval and applied to regions during which reflections occur, the effectiveness of the operator is disturbed and large errors of prediction result. This effect provides a method for the discrimination of reflections. The technique used has its basis in the theory of time series, relevant concepts of which are reviewed. The mechanics of application are given, and illustrative examples on ten seismograms are presented.

INTRODUCTION

Any variable which is generated sequentially in time constitutes a time series. This paper deals with modern methods of time-series analysis as applied to seismology. Although the underlying principles and basic techniques have been treated elsewhere in the literature, their potential contribution to seismology has not hitherto been exploited.

Credit for the first systematic study of time series belongs to Schuster, whose work on periodicities in geophysical data appeared at the turn of the century. Following Schuster, Yule (Ref. 2, 3) investigated economic time series from the viewpoint of difference equations, the use of which freed the subject from Schuster's assumption of strict periodicities.

In the late 1920's, Norbert Wiener studied this problem profoundly and produced his important paper on Generalized Harmonic Analysis in 1930. Some 10 years later, the concepts embodied in this paper were further developed by Wiener in the direction of prediction and filtering (Ref. 1).

Almost immediately upon the restricted publication of Wiener's work in 1942, a large-scale application of his methods to weather forecasting was undertaken in a project headed by Wadsworth at MIT. From 1942 until the present, Wadsworth and Bryan have been concerned with the application of suitable prediction techniques to non-stationary time series of relatively short duration. These results appear in a sequence of reports from 1942 to the present time. (Ref. 10, 11, 13, 14, 15, 16). In 1947 Wadsworth, collaborating with H. R. Seiwell, applied these statistical techniques to ocean wave research (Ref. 12). The success of the application of these techniques to this type of research led to the symposium on Applications of Autocorrelation Analysis[1] at Woods Hole, Mass. in June 1949.

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[1] An important contribution to this symposium was a paper by J. W. Tukey on sampling theory of power spectrum estimation.

In 1949 Hurley and Wadsworth discussed the problem of the statistical analysis of seismic information and preliminary examination was made of data then available. These results were sufficiently interesting so that more computations were made in the spring and summer of 1950 on seismic data supplied by the Magnolia Petroleum Company. During 1950 and 1951 Robinson had become interested in this subject and it was at that time that concentrated effort commenced in the study of linear operators and their usefulness in seismic record analysis.

The technique that is used in this paper is not exactly that of Wiener, since we are dealing with non-stationary processes. In some ways our approach is more general since some of the assumptions can be relaxed.

THE PROBABILISTIC APPROACH IN SEISMOLOGY

The Deterministic Approach and the Probabilistic Approach

There are two basic approaches to treating data observed in nature, and in particular the data represented on a seismogram. One is the deterministic approach and the other is the probabilistic approach. Many people think of these two approaches as conflicting, but actually this is not the case. Recent investigations indicate that each approach is fundamentally equivalent to the other.

Up to the present time the approach in seismology has been almost exclusively deterministic. In this approach deterministic methods are used to investigate laws connecting seismological phenomena. These laws are considered to be precise in action even though the observations on the quantities involved may be inaccurate and are certain to be incomplete.

On the other hand, the probabilistic approach utilizes quantities in the form in which they are observed. Distributions and statistical functions of these quantities are examined in such combinations as one chooses. Of course, one has considerable freedom in the selection of the quantities which are to form the subject of a statistical investigation.

Actually, in an ideally complete survey, one should investigate all possible statistical parameters and combinations of parameters and not merely a selection from among them. Unfortunately, such an undertaking would be impossible because of its sheer magnitude.

Therefore in a statistical investigation one should look for groups of parameters which are connected by rigid dynamic laws with each other and with the nature of the desired information. For such a group, some of the parameters would be determined by a knowledge of the remaining ones and the dynamics would be expressed as a statistical fact. If the dynamics are not so expressed, one can conclude either that a sufficient number of the significant statistical parameters have not been considered to give a true picture of the situation, or that these parameters have been observed so inaccurately that they can not give the true picture.

It is impossible for a significant dynamic relationship not to be brought out by a proper statistical examination of the relevant quantities. In fact, if certain simplifying assumptions have to be made in the derivation of dynamic laws by a deterministic approach, there are frequent cases where the probabilistic approach actually yields more information. Such a case might be as likely in seismology as it is in quantum theory and in statistical mechanics.

The Basic Problems

Exploration seismology can be broken down into logical steps which are presented graphically in Figure 1. We see that there are two mathematical approaches for the treatment of data, the deterministic approach and the probabilistic approach. The deterministic approach consists of utilizing physical theories of wave propagation involving the solutions of integral and differential

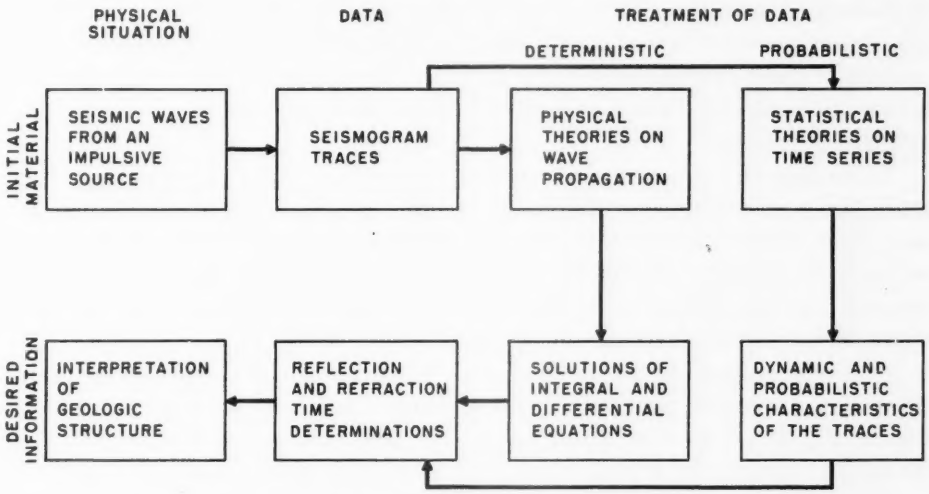

FIG. 1. The deterministic and probabilistic approaches to seismology.

equations satisfying boundary and initial conditions. The probabilistic approach consists of utilizing statistical theories of time series leading to the expression of the dynamics as a statistical fact.

The basic problems of our research program have not been solved, but nevertheless steps have been taken in that direction. Briefly, the basic problems deal with the determination of (1) statistical methods adequate to separate desired information from the total information present on the seismogram, (2) the relationship of desired information in statistical form with significant seismologic variables and the geologic structure, and (3) the interrelation of the deterministic and probabilistic approaches.

The Introduction of Statistical Methods to Seismology

This section deals with the first basic problem, namely, the determination of statistical methods adequate to separate desired information from the total information present on the seismogram. We consider statistical methods because a seismogram trace as recorded is a statistical time series, and all the traces on a seismic record constitute a set of multiple time series. This set of multiple time series is tied down to a specific origin in time, namely the time of the explosion. Time series with such a time origin dependence are called non-stationary, as opposed to stationary time series which are not linked to a specific origin in time.

Our research program in seismology was concerned with the evaluation of valid statistical methods in order to obtain the goal set forth in the first basic problem. Of all the statistical methods evaluated it was found that the application of linear operators was the most satisfactory method with regard to seismogram analysis. The method of utilizing linear operators is mathematically equivalent to the solution of a system of differential equations in space and time, but is more powerful in that it can cope effectively with disturbing influences of a random or quasi-random nature. By the use of linear operators the dynamic elements of the physical situation can be brought into sharp focus and disturbing elements suppressed.

As an approximate method of treating the non-stationary phenomenon represented by a seismogram, we divide the record into time intervals which may be considered approximately stationary. The traces in a given time interval, which we shall call the operator time interval, are used to determine an optimum linear operator for this interval. This linear operator contains, inherently, the dynamic characteristics of the traces in the operator time interval.

One type of linear operator which may be used is a pure prediction operator. That is, the operator predicts the future value of one trace from its past values and from past values of adjacent traces. The past values used as a basis of prediction are always the actual values taken from the seismic record, and are not previously predicted values corresponding to these actual values. Hence the input into the operator is always representative of the seismogram at any given point.

The ability of an operator to detect disturbances in the dynamics of the seismogram depends directly upon its accuracy in reconstructing the trace in the operator time interval. It was found that a multiple prediction operator which utilizes the traces from several geophone positions is superior to an operator which utilizes only one trace in its prediction mechanism. Having established the dynamic characteristics of the operator time interval by means of a linear operator, we wish to compare the dynamics of this interval with the rest of the seismogram. In order to accomplish this end, the operator is used to predict over the length of the seismic record in which we are interested.

The prediction error is defined as the difference between the predicted value and the actual value of the trace. This error gives a measure of the dynamic uni-

formity of the seismogram in the sense that low error, or good predictability, indicates small dynamical change, and large error indicates considerable dynamical change. Each conceivable operator generates a sequence of errors which forms a time series, which we may call the error time series. An investigation of these error time series, as we shall see, exposes the dynamics of the seismogram as a statistical fact. Such information about the dynamic characteristics constitutes desired information.

The Relationship of Statistical Information to Geologic Information

Once the dynamic characteristics of a seismic record are reduced by statistical methods into a statistical form, the next problem is to translate this statistical information into meaningful geologic information. This makes up the second basic problem of our research.

By computing linear operators over different sections of the record, it was found that the dynamic characteristics remained fairly consistent in the sense that one operator would apply to several sections except during intervals corresponding to a reflection. In other words, it was found that when an operator chosen for a non-reflection interval is applied to regions during which reflections occur, the effectiveness of the operator is disturbed and large errors of prediction result. Apparently, however, the disturbance is quickly assimilated, for the mechanism rapidly reverts to approximately the former level of prediction accuracy in the region following the reflection. Thus the error of prediction gives a measure of the extent to which a reflection changes the dynamic properties of a seismogram over a short interval. Therefore, by examining error time series or statistics computed from these error time series, one is able to pick off the arrival of reflected energy at places of high error. Such a procedure of analysis has been found to have two advantages: (1) the qualitative characteristics of reflections are better defined and (2) quantitatively, more reflections may be distinguished than by visual inspection of the seismogram. Illustrations of the measurement of prediction errors from ten records are presented in the section on Applications.

The problems to be explored in this direction include a more complete analysis of the reason why the dynamics of the seismograms change as they do. Various types of operators should be explored to determine which types are more sensitive to the location and discrimination of reflections. The variables which come under consideration may be subdivided into geologic variables, instrumental variables and mathematical variables. The geologic variables include such factors as underground structure, physical constants of the earth, and shot-hole effects. Instrumental variables include geophone layouts and response characteristics of the instrument used. Mathematical variables include the parameters of the linear operator and the statistics used to characterize the time series under consideration. It is necessary to investigate the effects of all these variables and to optimize those under our control.

The Interrelation of the Deterministic and Probabilistic Approaches

The third basic problem, namely, the interrelation of the probabilistic and deterministic approaches, is fundamental and also the most difficult of the problems. We have not considered this problem in detail but have it before us for future work.

One method of approach is the following. Given a physical situation which can be treated by exact physical theory, we shall introduce some random effects. From such a model a theoretical time series analysis could be carried out. In particular, the form of such statistical functions as the autocorrelation and cross-correlation could be derived from the physical situation.

Another method of approach is to determine what makes up the predictable component of the seismogram traces. The degree of predictability is intimately tied up with the stability of the operator, which in turn is tied up with the stability of the autocorrelation and cross-correlation functions. The stability of these functions depends upon the type of non-stationary time series generated by the geologic situation. The non-stationary character of these time series means that any differential equation which is set up to explain this phenomenon has variable coefficients which depend either upon time or upon the phenomenon itself. For optimum results the solution of the proper differential equation might be incorporated into the prediction mechanism.

CONCEPTS FROM THE THEORY OF STATIONARY TIME SERIES

Time Series Analysis

We shall now present some concepts from the theory of stationary time series. We are concerned chiefly with stating definitions and important theorems, and we shall by no means present a complete summary of the theory of time-series analysis. In particular we shall not deal with the important work of the so-called "English school" of statisticians, which bases its analysis on stochastic difference equations leading to the autoregressive time series (Ref. 2, 3, 4, and 5). Those many readers who are familiar with the concepts we present in this section may proceed directly to the section on Applications without losing the continuity of this paper.

The concepts given in this section depend upon the time series being stationary. A time series is said to be stationary if the probabilities involved are not tied down to a specific origin in time and if the series is conceived to run from minus infinity to infinity in time.

The Linear Operator

The one particular feature which makes the application of traditional statistical methods to time series analysis difficult is the absence of independence between successive observations. This lack of independence between successive observations is the fundamental characteristic of a time series. In the time series

observed in nature such interdependence is caused by neither completely random nor completely deterministic factors, but instead the motivating factors lie somewhere between these two extremes.

As a result the most direct procedure in the analysis of time series is one which exploits the lack of independence between successive observations. The use of an operator which depends upon the interdependence of observations in the time series is one such procedure. Operators may be linear or non-linear. Since the concept of linearity which is used is of the most general type and includes a wide range of time series, we deal with linear operators exclusively in this paper, although conceivably the use of non-linear operators may prove of greater applicability to seismogram analysis.

As an introduction to the concept of a linear operator we shall consider the pure sine series

$$u_t = A \sin (\omega_0 t + \theta). \tag{1}$$

Such a series is completely deterministic for it contains no random element. As a result there exists an identity connecting three consecutive observations which is given by

$$u_{t+2h} = a u_{t+h} + b u_t. \tag{2}$$

The constant a is equal to $2 \cos \omega_0 h$ and the constant b is equal to -1. The constants a and b constitute a linear operator whereby, from two consecutive values of the time series, all future values may be obtained.

It should be noted that the constants a and b of the linear operator are independent of the phase θ of the sine series. Hence the linear operator reveals the stationary character of the sine series in that the operator is not tied down to any particular origin in time. Also the operator is independent of the amplitude A which means that it is independent of the measurement used in the observations. Therefore we see that the linear operator represents an intrinsic property of the sine series, and it is not linked to the time origin or scale of the individual observations. These properties of a linear operator carry over for a large group of functions other than sines and cosines.

The Relationship of the Linear Operator and the Autocorrelation

Such an operator, which is linear, invariant with respect to the origin in time, and dependent only on the past history of the time series, is the type which Prof. N. Wiener considers in his theory of prediction for stationary time series (Ref. 1, Chapter II). He approximates the future value $f(t+\alpha)$ of the time series by applying a linear operator $K(\tau)$ to the past values $f(t-\tau)$ by means of the expression

$$\int_0^\infty f(t - \tau) dK(\tau). \tag{3}$$

The linear operator $K(\tau)$ is determined by minimizing the mean square error, which is given by

$$\lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{T}\left|f(t+\alpha) - \int_{0}^{\infty} f(t-\tau)dK(\tau)\right|^2 dt. \tag{4}$$

Utilizing the calculus of variations for this minimization process, he obtains the integral equation

$$\phi(\alpha+\tau) = \int_{0}^{\infty}\phi(\tau-\sigma)dK(\sigma) \quad \text{for} \quad \tau > 0. \tag{5}$$

Here $\phi(\tau)$ is defined by

$$\phi(\tau) = \lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{T} f(t)f(t+\tau)dt \tag{6}$$

and is called the autocorrelation function. Hence equation (5) tells us that the linear operator $K(\tau)$ is determined from the autocorrelation function $\phi(\tau)$. The autocorrelation function represents intrinsic dynamic properties of the time series.

The Spectrum

The fundamental theorem of generalized harmonic analysis, due to Prof. N. Wiener (Ref. 1, Chapter I), relates the autocorrelation function $\phi(\tau)$ with a monotone increasing function $\Lambda(\omega)$. More precisely, if the autocorrelation function $\phi(\tau)$ exists, then there exists a monotone increasing function $\Lambda(\omega)$ which is given by the Fourier transform

$$\phi(\tau) = \int_{-\infty}^{\infty} e^{i\omega\tau}d\Lambda(\omega). \tag{7}$$

The function $\Lambda(\omega)$ is called the integrated spectrum or integrated periodogram of $f(t)$, and represents the total power in the spectrum of $f(t)$ between the frequency $\omega = -\infty$ and the frequency ω. The integrated spectrum $\Lambda(\omega)$ may have a series of jumps if there are exact frequencies or spectral lines in the function $f(t)$. Otherwise $\Lambda(\omega)$ will be continuous, and this is the usual case met in applications.

If $\Lambda(\omega)$ is differentiable, its derivative $\Lambda'(\omega) = \Phi(\omega)$ is called the spectrum of the function $f(t)$. We may then write the Fourier transform

$$\phi(\tau) = \int_{-\infty}^{\infty} e^{i\omega\tau}\Phi(\omega)d\omega \tag{8}$$

and, in the case of simple functions, the inverse transform

$$\Phi(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-i\omega\tau}\phi(\tau)d\tau. \tag{9}$$

Since in this case both $\phi(\tau)$ and $\Phi(\omega)$ are even functions we may rewrite equations (8) and (9) as

$$\phi(\tau) = 2\int_{0}^{\infty} \cos\,\omega\tau\Phi(\omega)d\omega \tag{10}$$

and

$$\Phi(\omega) = \frac{1}{\pi}\int_{0}^{\infty} \cos\,\omega\tau\phi(\tau)d\tau. \tag{11}$$

Thus the autocorrelation function gives information about $f(t)$ which is analogous to the spectrum. More precisely, information as to the frequencies of $f(t)$ is preserved, and information as to the phases of the individual frequencies is lost, both in the autocorrelation function and in the spectrum.

By setting $\tau=0$, equations (6) and (8) reduce to

$$\phi(0) = \lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{T} f^2(t)dt = \int_{-\infty}^{\infty} \Phi(\omega)d\omega. \tag{12}$$

Hence we see that the total power in the spectrum is given by $\phi(0)$. The customary statistical practice is to normalize the autocorrelation function and spectrum by normalizing $f(t)$ so that it has zero mean and unit variance in the time-average sense. Then $\phi(0)=1$ and $|\phi(\tau)| \leqq 1$, and the total power in the spectrum is equal to one.

The Relationship of the Autocorrelation and the Spectrum

We shall now give a few examples illustrating the relationship as given in equations (10) and (11) between the autocorrelation function and the spectrum.

The first example is that of the pure sine series given by equation (1). This series is completely deterministic for it contains no random element. The normalized autocorrelation of this series, computed from equation (6), is given by

$$\phi(\tau) = \cos\,\omega_0\tau, \tag{13}$$

which is an undamped cosine wave. The Fourier transform does not exist, but from classical Fourier series methods it can be shown that the spectrum is a line spectrum in which all the power is concentrated at the frequency ω_0.

This example allows us to give an heuristic interpretation to the relationships of the autocorrelation function and spectrum given in equation (10). Consider the spectrum $\Phi(\omega)$ of an arbitrary time series $f(t)$. Each small band of frequencies between ω and $\omega+d\omega$ acts with the differential power $\Phi(\omega)d\omega$. In view of equation (13), the differential transform of the small band of frequencies is given by

$\cos \omega\tau\Phi(\omega)d\omega$. This differential is the contribution of the small band of frequencies between ω and $\omega+d\omega$ to the autocorrelation function. Summing these differential transforms from $\omega=-\infty$ to $\omega=\infty$ we obtain the integral for the autocorrelation $\phi(\tau)$ given in equation (10).

The second example is that of a random series. A random series is conceived to have a "white light" spectrum; that is, the spectrum is given by a rectangular distribution over a long range R. Let the spectrum be

$$\Phi(\omega) = \frac{1}{2R} \tag{14}$$

for the range given by $-(a+R) \leqq \omega \leqq -a \leqq 0$ and $0 \leqq a \leqq \omega \leqq a+R$, and let $\Phi(\omega)=0$ for values of ω outside of this range. Then the normalized autocorrelation is given by

$$\phi(\tau) = \frac{2}{R\tau} \sin \frac{R\tau}{2} \cos \left[a\tau + \frac{R\tau}{2} \right]. \tag{15}$$

We note that as R tends toward zero, $\phi(\tau)$ tends toward $\cos a\tau$, which is expected in view of equation (13).

The third example is the case of pure persistence in a time series. In this case the normalized autocorrelation function is given by the exponential

$$\phi(\tau) = e^{-a|\tau|}, \qquad a > 0 \tag{16}$$

and the spectrum by the Cauchy curve

$$\Phi(\omega) = \frac{1}{\pi} \frac{a}{a^2 + \omega^2}. \tag{17}$$

Hence we see that all frequencies exist from $\omega=-\infty$ to $\omega=+\infty$.

The last example is the case in which the spectrum is the mean of two normal (Gaussian) distributions, that is,

$$\Phi(\omega) = \frac{1}{2\sigma\sqrt{2\pi}} e^{-(\omega+a)^2/2\sigma^2} + \frac{1}{2\sigma\sqrt{2\pi}} e^{-(\omega-a)^2/2\sigma^2}. \tag{18}$$

Then the normalized autocorrelation is given by

$$\phi(\tau) = e^{-\sigma^2\tau^2/2} \cos a\tau, \tag{19}$$

which is a damped cosine wave.

The Relationship of the Linear Operator and the Cross-correlation

The discussion to this point has concerned itself with the statistical properties of a single stationary time series $f(t)$. We now wish to extend these concepts to the case where we have multiple stationary time series.

A linear operator for this case is defined in a way analogous to the case of single time series. It predicts the future of one time series from its past values and the past values of the other time series. The minimization of the mean square error for the general case is carried out by N. Wiener (Ref. 1, Chapter IV). It is shown that the linear operator depends only on the autocorrelation and cross-correlations of the time series considered. The cross-correlation function is a property of two time series $f_1(t)$ and $f_2(t)$, and is defined in a way similar to the autocorrelation function by

$$\phi_{12}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} f_1(t) f_2(t+\tau)\, dt. \tag{20}$$

The cross-correlation between $f_2(t)$ and $f_1(t)$ is defined as

$$\phi_{21}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} f_2(t) f_1(t+\tau)\, dt. \tag{21}$$

From the definitions (20) and (21) it follows that

$$\phi_{12}(\tau) = \phi_{21}(-\tau). \tag{22}$$

In statistical practice the cross-correlation function is usually normalized by letting both $f_1(t)$ and $f_2(t)$ have zero mean and unit variance in the time-average sense. Then we have $|\phi_{11}(\tau)| \leqq 1$ and $|\phi_{22}(\tau)| \leqq 1$. Using the Schwarz inequality, we have the desired normalization of the cross-correlation which is $|\phi_{12}(\tau)| \leqq 1$.

The Cross-spectrum

The cross-correlation function $\phi_{12}(\tau)$ of $f_1(t)$ and $f_2(t)$ may be expressed as the Fourier transform

$$\phi_{12}(\tau) = \int_{-\infty}^{\infty} e^{i\omega\tau} \Phi_{12}(\omega)\, d\omega. \tag{23}$$

Here $\Phi_{12}(\omega)$ is defined to be the cross-spectrum of $f_1(t)$ and $f_2(t)$. In the case of simple functions, the inverse transform may be written as

$$\Phi_{12}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-i\omega\tau} \phi_{12}(\tau)\, d\tau. \tag{24}$$

In general, the cross-correlation function $\phi_{12}(\tau)$ is not an even function of τ, and hence equation (24) tells us that the cross-spectrum $\Phi_{12}(\omega)$ has real and imaginary parts. Equations analogous to (23) and (24) hold for the cross-correlation $\phi_{21}(\tau)$ and the cross-spectrum $\Phi_{21}(\omega)$ between the time series $f_2(t)$ and $f_1(t)$. From these relations we find that

$$\Phi_{12}(\omega) = \overline{\Phi_{21}(\omega)}, \tag{25}$$

where the bar indicates the complex conjugate.

Since the cross-spectrum $\Phi_{12}(\omega)$ is a complex-valued function of the real variable ω we may write

$$\Phi_{12}(\omega) = \text{Re}\,[\Phi_{12}(\omega)] + i\,\text{Im}\,[\Phi_{12}(\omega)] \tag{26}$$

where $Re[\Phi_{12}(\omega)]$ designates the real part, and $Im[\Phi_{12}(\omega)]$ designates the imaginary part, of the cross-spectrum. We may also express the cross-spectrum by

$$\Phi_{12}(\omega) = |\,\Phi_{12}(\omega)\,|\,e^{i\theta(\omega)}. \tag{27}$$

Here $|\,\Phi_{12}(\omega)|$ designates the absolute value of the cross-spectrum, and is given by

$$|\,\Phi_{12}(\omega)\,| = \sqrt{[\text{Re}\,(\Phi_{12})]^2 + [\text{Im}\,(\Phi_{12})]^2}. \tag{28}$$

The argument $\theta(\omega)$ of the cross-spectrum is a function of the frequency ω, and is given by

$$\theta(\omega) = \text{arc tan}\,\frac{\text{Im}\,[\Phi_{12}(\omega)]}{\text{Re}\,[\Phi_{12}(\omega)]}. \tag{29}$$

Let the spectrum of $f_1(t)$ be $\Phi_{11}(\omega)$ and the spectrum of $f_2(t)$ be $\Phi_{22}(\omega)$. It can be shown (see Appendix) that the absolute value of the cross-spectrum is given by the geometric mean of the individual spectra, that is

$$|\,\Phi_{12}(\omega)\,| = \sqrt{\Phi_{11}(\omega)}\,\sqrt{\Phi_{22}(\omega)}. \tag{30}$$

Hence we see that the cross-spectrum preserves only the common frequencies of $f_1(t)$ and $f_2(t)$.

Let $\theta_1(\omega)$ represent the phase angle of the frequency ω in the time series $f_1t)$, and let $\theta_2(\omega)$ represent the phase angle of the frequency ω in the time series $f_2(t)$. The phase angles $\theta_1(\omega)$ and $\theta_2(\omega)$ depend upon the time origin of the individual time series $f_1(t)$ and $f_2(t)$ respectively. It can be shown (see Appendix) that the argument $\theta(\omega)$ of the cross-spectrum $\Phi_{12}(\omega)$ is given by the difference of the phase angles of the individual time series, that is

$$\theta(\omega) = \theta_1(\omega) - \theta_2(\omega). \tag{31}$$

The difference $\theta_1(\omega) - \theta_2(\omega)$ is independent of the time origin of the individual time series $f_1(t)$ and $f_2(t)$, and hence the stationary character of the cross-correlation and the cross-spectrum is indicated. Thus the phase differences of common frequencies of the two individual time series are preserved in the cross-spectrum.

Equations (23) and (24) show that the cross-spectrum $\Phi_{12}(\omega)$ gives information about $f_1(t)$ and $f_2(t)$ which is analogous to the cross-correlation $\Phi_{12}(\tau)$. Hence, information as to frequencies common to $f_1(t)$ and $f_2(t)$ is preserved, and information as to the phase differences of these common frequencies is preserved, both in the cross-spectrum and cross-correlation.

The Relationship of the Cross-correlation and the Spectra

Substituting equations (30) and (31) into equation (27), we see that the cross-spectrum is given by

$$\Phi_{12}(\omega) = \sqrt{\Phi_{11}(\omega)}\sqrt{\Phi_{22}(\omega)}\, e^{i[\theta_1(\omega)-\theta_2(\omega)]}. \tag{32}$$

Substituting this equation into equation (23) we find that the desired relationship between the cross-correlation and the spectra is given by

$$\phi_{12}(\tau) = \int_{-\infty}^{\infty} \sqrt{\Phi_{11}(\omega)}\sqrt{\Phi_{22}(\omega)} \cos\,[\omega\tau + \theta_1(\omega) - \theta_2(\omega)]d\omega. \tag{33}$$

This relationship may be interpreted heuristically as follows. Let us consider the two time series given by the sine functions $A \sin(\omega_1 t+\theta_1)$ and $B \sin(\omega_2 t+\theta_2)$. From the definition (20) of the cross-correlation, we see that the cross-correlation of these two sine functions is zero unless $\omega_1=\omega_2$. If $\omega_1=\omega_2$ then their cross-correlation, when normalized, becomes

$$\cos\,[\omega_1\tau + \theta_1 - \theta_2]. \tag{34}$$

Hence we see that their cross-correlation depends on the phase difference of their common frequency ω_1.

Let us now consider two arbitrary time series $f_1(t)$ and $f_2(t)$. Each small band of frequencies between ω and $\omega+d\omega$ acts with the differential power

$$|\,\Phi_{12}(\omega)\,|\,d\omega = \sqrt{\Phi_{11}(\omega)}\sqrt{\Phi_{22}(\omega)}\,d\omega. \tag{35}$$

Let the phase difference of the small band of frequencies in $f_1(t)$ and in $f_2(t)$ be given by $\theta_1(\omega)-\theta_2(\omega)$. In view of equation (34), we see that the differential transform of the small band of frequencies is given by

$$\sqrt{\Phi_{11}(\omega)}\sqrt{\Phi_{22}(\omega)} \cos\,[\omega\tau + \theta_1(\omega) - \theta_2(\omega)]d\omega. \tag{36}$$

This differential is the contribution of the small band of frequencies between ω and $\omega+d\omega$ to the cross-correlation function. Summing these differential transforms from $\omega=-\infty$ to $\omega=\infty$ we obtain the integral for the cross-correlation $\phi_{12}(\tau)$ given in equation (33).

In closing this section, which deals with concepts from the theory of stationary time series, we mention the following interesting example. Consider the purely random series $u_1, u_2, u_3, \cdots$ and the purely random series $v_1, v_2, v_3, \cdots$, in which the v_1 series is defined by the relationship $v_i=u_{i-j}$. Then it is seen that the cross-correlation of the two series is zero everywhere except at the jth lag, where the cross-correlation is equal to one. Such an example illustrates the value of the cross-correlation function in determining phase relationships.

APPLICATIONS TO SEISMOGRAM ANALYSIS

The Linear Operator Employed

We now present the mechanics of the statistical method described in the section on the Probabilistic Approach. As pointed out there, seismogram traces are non-stationary time series. Our statistical method for the analysis of these time series is the method of multiple correlation. Such a technique yields nearly the maximum amount of linear predictability in a finite time interval. This method differs from the Fourier methods developed by Professor Wiener for stationary time series in that he takes the entire past of the function as the basis of prediction.

In order to simplify notation we shall consider only two traces on the seismogram, but our presentation should allow the reader to extend the analysis to more than two traces. Let two traces be represented by $f_1(t)$ and $f_2(t)$ where t is time in seconds from the explosion. For computational purposes a discrete series is usually preferred, and by picking the time interval h between observations small enough a continuous trace may be transformed into a discrete series without losing essential information. Let $x_i=f_1(ih)$ and $y_i=f_2(ih)$ where h is the time unit of a discrete time series.

By the method of multiple correlation we wish to fit a linear operator to a time interval of the seismogram. This time interval, which we shall call the operator time interval, has a time duration of nh seconds and consists of the values x_i and y_i from $i=N$ to $i=N+n-1$.

The linear operator is one which predicts the future of trace x from its past values and from corresponding past values of trace y. Algebraically the operator is expressed as

$$\hat{x}_{i+k} = c + \sum_{s=0}^{M} (a_s x_{i-s} + b_s y_{i-s}). \tag{37}$$

In this expression $\hat{x}_{i+k}$ is the approximated value of the future value x_{i+k}, where k is the number of time units ahead which the operator predicts. That is, the prediction distance is given by kh. The $M+1$ past values of trace x are given by x_{i-s} where $s=0, 1, \cdots, M$, and the corresponding $M+1$ past values of trace y are given by y_{i-s} where $s=0, 1, \cdots, M$. The $2M+3$ constants of the operator given by c, a_s, and b_s ($s=0, 1, \cdots, M$) are constants determined in an optimum sense.

As is customary in the method of multiple correlation, these constants are determined by the Gauss method of least squares. Hence we wish to find the values of c, a_s, b_s ($s=0, 1, \cdots, M$) which minimize the sum of square errors between the actual value x_{i+k} and the predicted value $\hat{x}_{i+k}$. The summation is taken over the operator time interval; that is, the summation index $i+k$ should run from $i+k=N$ to $i+k=N+n-1$. Here we wish to minimize

$$I = \sum_{i=N-k}^{N+n-1-k} (x_{i+k} - \hat{x}_{i+k})^2 \tag{38}$$

with respect to c, a_s, b_s ($s=0, 1, \cdots, M$). Substituting equation (37) into equation (38) we have

$$I = \sum_i \left[x_{i+k} - c - \sum_s (a_s x_{i-s} + b_s y_{i-s}) \right]^2. \tag{39}$$

In equation (39), and from now on all summations on the index i are for $i=N-k$ to $i=N+n-1-k$, and all summations on the index s are for $s=0$ to $s=M$.

In order to carry out the minimization we set the partial derivatives of I with respect to c, a_s, b_s ($s=0, 1, \cdots, M$) equal to zero. Since there are $(M+1)a$'s, $(M+1)b$'s, and one c, we obtain $2M+3$ linear algebraic equations in the $2M+3$ unknowns given by a_s, b_s, c (where $s=0, 1, \cdots, M$). This set of simultaneous equations is

$$cn + \sum_s \left(a_s \sum_i x_{i-s} + b_s \sum_i y_{i-s} \right) = \sum_i x_{i+k}$$

$$c \sum_i x_{i-r} + \sum_s \left(a_s \sum_i x_{i-r} x_{i-s} + b_s \sum_i x_{i-r} y_{i-s} \right) = \sum_i x_{i-r} x_{i+k}$$

$$\text{for } r = 0, 1, \cdots, M \tag{40}$$

$$c \sum_i y_{i-r} + \sum_s \left(a_s \sum_i y_{i-r} x_{i-s} + b_s \sum_i y_{i-r} y_{i-s} \right) = \sum_i y_{i-r} x_{i+k}$$

$$\text{for } r = 0, 1, \cdots, M.$$

Expanding equation (39) and using equations (40) we see that the minimum value I_m of I is given by

$$I_m = \sum_i x_{i+k}^2 - c \sum_i x_{i+k} - \sum_s \left[a_s \sum_i x_{i-s} x_{i+k} + b_s \sum_i y_{i-s} x_{i+k} \right]. \tag{41}$$

The minimum value I_m is one measure of how well the operator reproduces the x series in the operator time interval.

We define the sample variance I_0 to be

$$I_0 = \sum_i (x_{i+k} - \bar{x})^2 \tag{42}$$

where $\bar{x} = 1/n \sum x_{i+k}$ is the sample mean of the x series in the operator time interval. Then the percent reduction of the sample variance about the sample mean is defined to be

$$\text{percent } R = 100 \left[1 - \frac{I_m}{I_0} \right]. \tag{43}$$

The percent reduction is another measure of how well the operator reproduces the x trace in the operator time interval, where one hundred percent reduction is perfect reproduction.

The Measure of Error of Prediction

Once numerical values of the constants a_s, b_s, c ($s=0, 1, \cdots, M$) of the operator are determined, they are used to predict the whole of trace x by means of equation (37). In using equation (37) it must be remembered that the past values of x_{i-s} and y_{i-s} (where $s=0, 1, \cdots, M$) are the actual values taken from the seismogram traces.

In order to determine how well trace x is being predicted by the operator the error between the actual value x_{i+k} and the predicted value $\hat{x}_{i+k}$ should be measured. These errors, or residuals, may be studied individually or statistically in order to measure the effectiveness of the operator in reconstructing the x trace.

One such statistical quantity which may be used is the running average E_i of square errors given by

$$E_i = \frac{1}{2p} \sum_{j=i-p}^{i+p-1} (x_j - \hat{x}_j)^2 \tag{44}$$

where $2p$ is the number of elements in each average. If we let

$$V_i^{(x)} = \frac{1}{2p} \sum_{j=i-p}^{i+p-1} (x_j - \bar{x})^2 \tag{45}$$

denote the running variance of trace x, then another measure of the goodness of the prediction of the x trace is the running reduction R_i given by

$$R_i = 1 - \frac{E_i}{V_i^{(x)}} \cdot \tag{46}$$

A third measure of the goodness of prediction of the x trace is given by

$$T_i = \frac{E_i}{\alpha V_i^{(x)} + \beta V_i^{(y)}} \tag{47}$$

where $V_i^{(x)}$ is the running variance of trace x and $V_i^{(y)}$ is the running variance of trace y. Here α and β are weighting factors which should be determined in an optimum sense with respect to the operator coefficients.

The three measures of the effectiveness of prediction given by equations (44), (46), and (47) were used in the computational studies in the summer and fall of 1951. Nevertheless, since the seismograms were A.V.C. (automatic volume control) records, the error curves E_i given by equation (44) were considered satisfactory as a first approximation to the measurement of prediction error.

The averages given in equations (44), (46), and (47) represent time averages of a single error time series. If we have many operators predicting several traces

another type of averaging is possible on the "ensemble" of error time series generated by these operators. An ensemble average, or an average across these series rather than along an individual one, is another measure of prediction error.

Let us suppose that we have taken a series of operators on a record which consists of traces from equally spaced seismometers. Suppose there are T traces, and on the l^{th} trace ($l = 1, 2, \cdots T$) we have chosen N_l operators. For the k^{th} operator on this trace ($k = 1, \cdots N_l$) there is an associated error time series which we define as $e_i(kl)$. Then, for example, we may construct a single error time series $\epsilon_i{}^l$ to be associated with the l^{th} trace by the expression

$$\epsilon_i{}^l = \sum_{k=1}^{Nl} \left[e_i{}^{(kl)}\right]^2. \tag{48}$$

We may then average these error time series over the various traces. Now since we are interested not only in finding reflection times but also the associated step-outs, we construct the error time series $\delta_i{}^{(\alpha)}$ with an arbitrary lag or lead α

$$\delta_i{}^{(\alpha)} = \sum_{l=1}^{T} \epsilon_{i-\alpha l}{}^{(l)} \qquad \alpha = 0, \pm 1, \pm 2, \cdots \tag{49}$$

with the expectation that a peak on this error time series, corresponding to a certain reflection, should be highest and narrowest for that value of α most closely corresponding to the true step-out of the given reflection. At the present time a study is being made on the use of ensemble averaging of this type.

COMPUTATIONAL RESULTS

The Tukey-Hamming Computational Procedure to Estimate the Spectrum

In 1950 and 1951 computational studies were undertaken to determine the statistical properties of the correlation functions and the spectra taken over various intervals of seismic records. We shall not reproduce the specific results from these studies in this paper. Nevertheless, we should like to present Tukey's method of computing the spectrum. It should be pointed out that this method was developed by Tukey (Ref. 6), and Tukey and Hamming (Ref. 7), so that the spectra of short time series could be estimated with a knowledge of the variability of the estimate.

The unnormalized autocorrelation of a group of data at equally spaced intervals of time, say x_1, $x_2 \cdots x_n$, are computed by the standard formulae. The formula which Tukey prefers is given by

$$R_p = \frac{1}{N - p} \sum_{i=1}^{N-p} x_i x_{i+p} \tag{50}$$

Here the R_p's are estimates of the unnormalized autocorrelation function at the discrete lag p, and are called the sample serial products.

The basic problem is to obtain an approximation to the spectrum from a given number m of these serial products computed from a finite time series. Frequencies ω and frequencies $2\pi \pm \omega$, $4\pi \pm \omega$, etc., are equivalent as far as the method of Tukey and Hamming is concerned. Thus the effect is to fold over the last part of the frequency scale where $2\pi/\omega < 2$ into that portion of the scale where $2\pi/\omega \geq 2$. This means of course that on the ω scale the distribution of frequencies will now run from $-\pi$ to π, and we shall confine our attention to this region. By choosing discrete values of angular frequency $\omega = s\pi/m$ ($s = 0, 1, 2, \cdots, m$), we may perform numerical integration of (11) by the trapezoidal rule and write

$$\Phi\left(\frac{s\pi}{m}\right) \approx L_s \tag{51}$$

where

$$L_s = \frac{1}{\pi}\left[\frac{1}{2} R_0 \cos 0 + \sum_{j=1}^{m-1} R_j \cos \frac{s\pi j}{m} + \frac{1}{2} R_m \cos s\pi\right]. \tag{52}$$

By letting $r_j = R_j/R_0$ ($j = 0, 1, \cdots, m$), we have

$$L_s = \frac{R_0}{2\pi}\left[1 + 2\sum_{j=1}^{m-1} r_j \cos \frac{s\pi j}{m} + r_m \cos s\pi\right]. \tag{53}$$

An approximate integration of $\Phi(\omega)$ from $-\pi$ to π by the trapezoidal rule yields

$$\int_{-\pi}^{\pi} \Phi(\omega)d\omega = 2\int_{0}^{\pi} \Phi(\omega)d\omega \approx \frac{\pi}{m}\left[L_0 + 2\sum_{1}^{m-1} L_s + L_m\right]. \tag{54}$$

Now by standard summation formulae, we find that

$$L_0 + 2\sum_{1}^{m-1} L_s + L_m = \frac{m}{\pi} R_0. \tag{55}$$

Thus, for all values of m, the area given by the trapezoidal rule is R_0, the serial product of lag zero. Since R_0 is the computed estimate of $\phi(0)$, the trapezoidal approximation of equation (11) yields the statistical analogue of equation (12). Moreover we see, once again, that in the estimated spectrum the total power has been compressed into the interval $(-\pi, \pi)$.

Because the values of L_s are subject to systematic statistical errors, they must be smoothed in order to obtain a satisfactory estimate of the spectral density. After research into feasible smoothing techniques, Tukey and Hamming settled upon the following simple scheme. The smoothed estimate U_s of the spectral density is given by

$$U_s = .23L_{s-1} + .54L_s + .23L_{s+1} \quad (s = 0, 1, 2, \cdots, m). \tag{56}$$

Since U_0 and U_m respectively involve L_{-1} and L_{m+1}, which have not been defined, set $L_{-1} = L_1$ and $L_{m+1} = L_{m-1}$. Or what amounts to the same thing, smooth the end points thus:

$$\begin{aligned} U_0 &= .54L_0 + .46L_1 \\ U_m &= .54L_m + .46L_{m-1}. \end{aligned} \tag{57}$$

Because of the identity

$$U_0 + 2\sum_{1}^{m-1} U_s + U_m = L_0 + 2\sum_{1}^{m-1} L_s + L_m \tag{58}$$

we see that the smoothing process is area-preserving, and that the statistical analogue of equation (12) also holds for the smoothed estimates U_s.

Examples of Correlation Functions and Spectra

In Figures 2 and 3 we present examples of correlation functions and spectra. The solid curve in the left hand side of Figure 2 shows an autocorrelation function for trace N750 of MIT Record No. 2 (Figure 4) from time equal to .2 seconds to 1.2 seconds; and the dashed curve shows corresponding autocorrelations for trace S750. Both of these autocorrelation functions have been normalized so that their zeroth lag is equal to one. Utilizing the computational procedure of Tukey and Hamming the spectra of each of these traces were computed from their autocorrelation functions. These spectra, which are shown in the right hand side of Figure 2, have not been normalized; hence their areas represent the relative energies present in the traces.

A second example of correlation functions and spectra is presented in Figure 3. We let $f_1(t)$ represent trace N750 on MIT Record No. 1 (Figure 4) from time equal to 1.05 seconds to 1.225 seconds, and $f_2(t)$ represent trace N250 over the same interval of time. These two traces were divided into a discrete series of observations, with a spacing of 2.5 milliseconds between observations. These traces were measured in arbitrary units of amplitude about their mean values.

In diagram A of Figure 3 the solid curve shows the autocorrelation function $\phi_{11}(\tau)$ of trace N750, and the dashed curve shows the autocorrelation function $\phi_{22}(\tau)$ of trace N250. These autocorrelation functions, which are not normalized, were estimated by the serial products of the traces. In diagram B of Figure 3 the solid curve shows the spectrum $\Phi_{11}(\omega)$ of trace N750; and the dashed curve shows the spectrum $\Phi_{22}(\omega)$ of trace N250. These spectra were estimated from the autocorrelation functions given in diagram A by use of the Tukey-Hamming computational procedure.

Diagram C of Figure 3 gives the cross-correlation function $\phi_{12}(\tau)$ of trace N750 and trace N250. The cross-correlation function, which is not normalized, was estimated by the cross products of the two traces. Diagram D of Figure 3 gives the cross spectrum $\Phi_{12}(\omega)$ of trace N750 and trace N250. The cross-spectrum

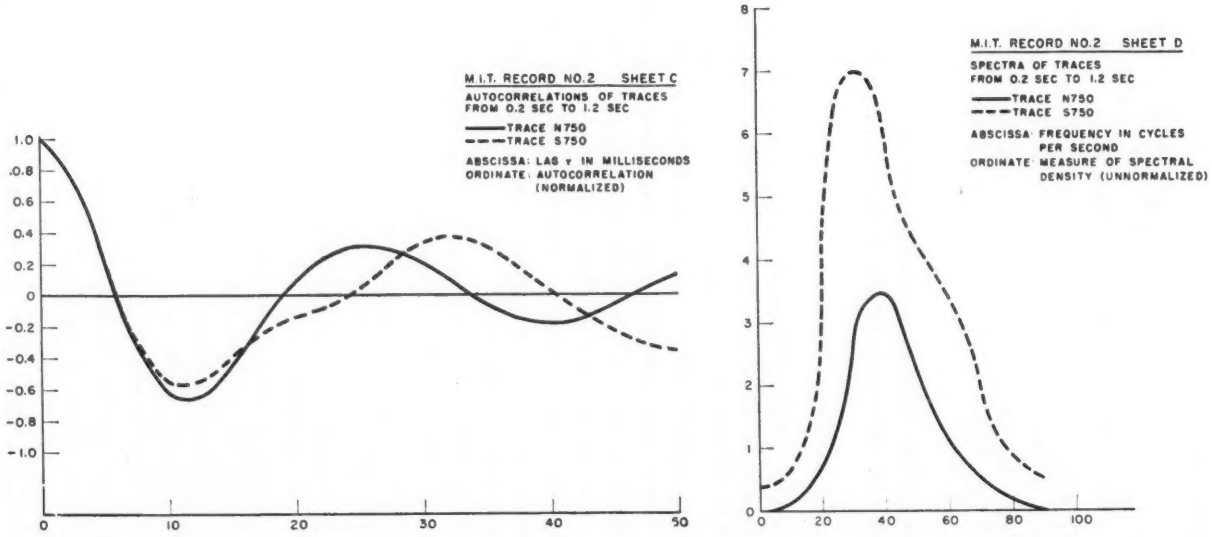

FIG. 2. Examples of autocorrelations and spectra, on MIT Record No. 2 from time equal to 0.2 second to 1.2 seconds.

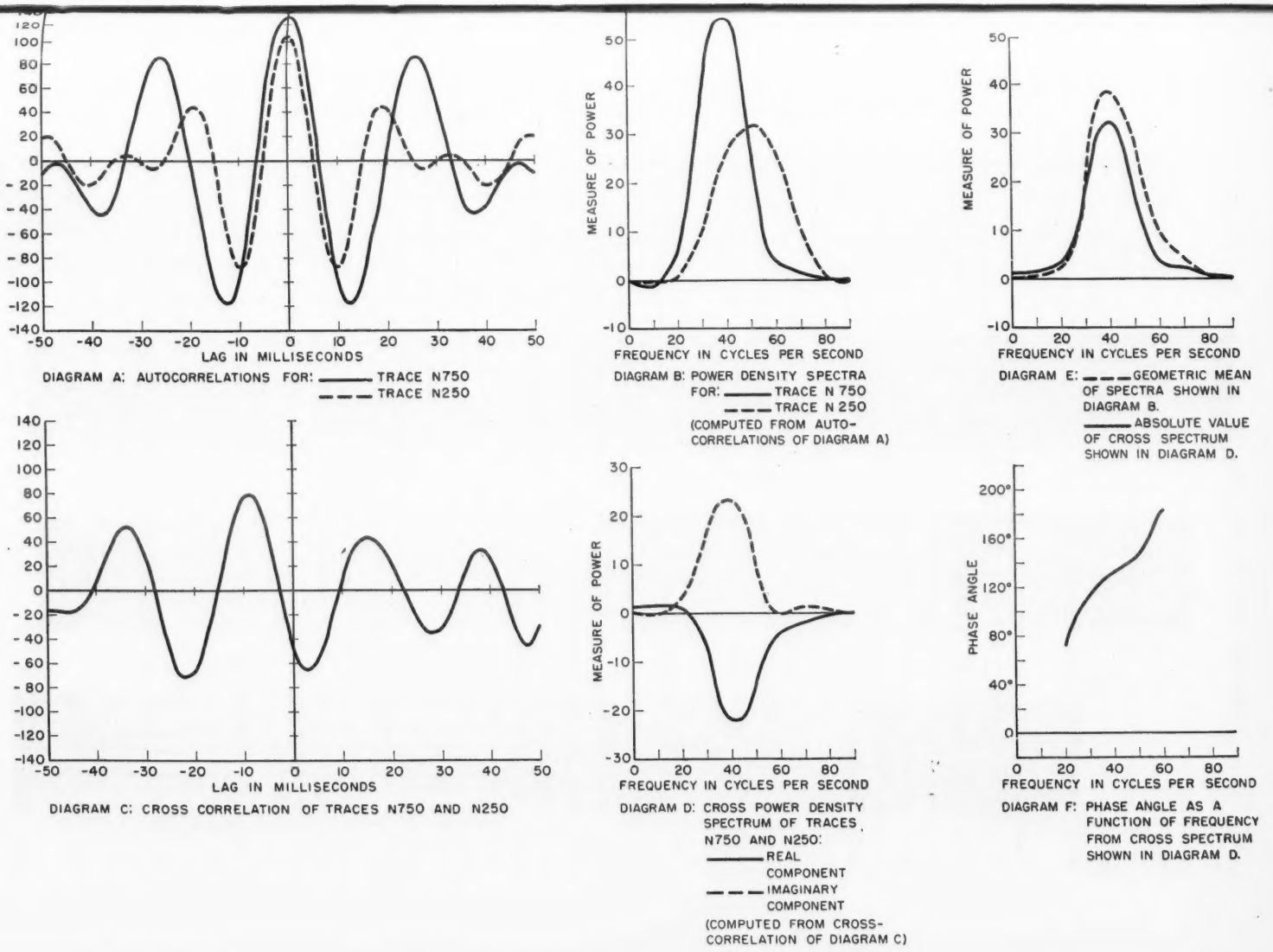
LAG IN MILLISECONDS
DIAGRAM A: AUTOCORRELATIONS FOR: ——— TRACE N750
– – – TRACE N250
MEASURE OF POWER
FREQUENCY IN CYCLES PER SECOND
DIAGRAM B: POWER DENSITY SPECTRA FOR: ——— TRACE N 750
– – – TRACE N 250
(COMPUTED FROM AUTO-CORRELATIONS OF DIAGRAM A)
DIAGRAM E: – – – GEOMETRIC MEAN OF SPECTRA SHOWN IN DIAGRAM B.
——— ABSOLUTE VALUE OF CROSS SPECTRUM SHOWN IN DIAGRAM D.
LAG IN MILLISECONDS
DIAGRAM C: CROSS CORRELATION OF TRACES N750 AND N250
MEASURE OF POWER
FREQUENCY IN CYCLES PER SECOND
DIAGRAM D: CROSS POWER DENSITY SPECTRUM OF TRACES N750 AND N250:
——— REAL COMPONENT
– – – IMAGINARY COMPONENT
(COMPUTED FROM CROSS-CORRELATION OF DIAGRAM C)
PHASE ANGLE
FREQUENCY IN CYCLES PER SECOND
DIAGRAM F: PHASE ANGLE AS A FUNCTION OF FREQUENCY FROM CROSS SPECTRUM SHOWN IN DIAGRAM D.

FIG. 3. Examples of correlation functions and spectra, on MIT Record No. 1 from time equal to 1.05 seconds to 1.225 seconds.

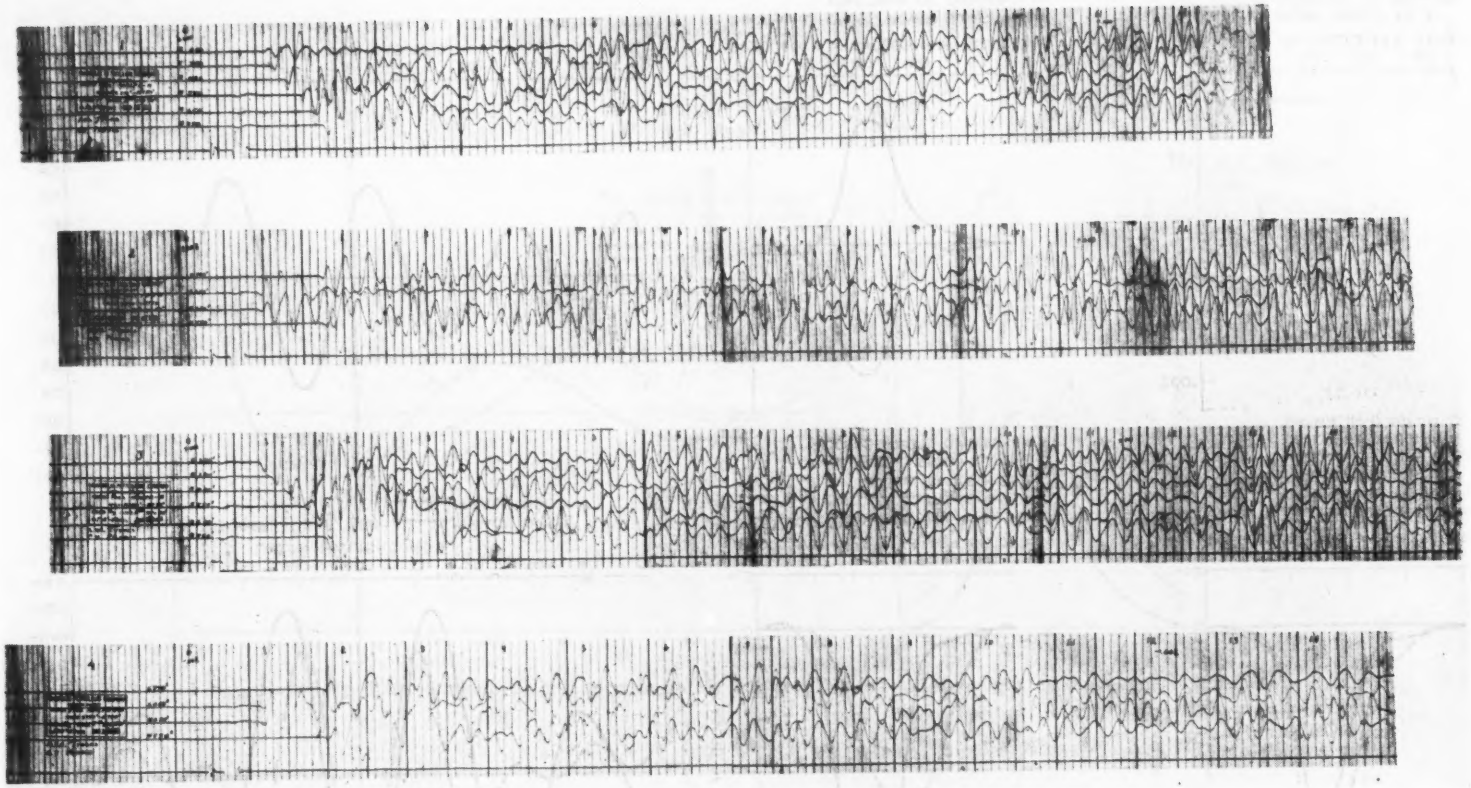

FIG. 4. MIT Records No. 1, 2, 3, and 4. (Furnished by Magnolia Petroleum Co.)

was estimated from the cross-correlation given in diagram C by an extension of the Tukey-Hamming computational procedure to equation (24). Since the cross-correlation function is not an even function of the lag τ, the cross-spectrum has real and imaginary parts. In diagram D of Figure 3 the real part of the cross-spectrum is shown by the solid curve, and the imaginary part is shown by the dashed curve.

The dashed curve of diagram E shows the geometric mean of the individual spectra shown in diagram B. The solid curve in diagram E shows the absolute value of the cross-spectrum which is shown in diagram D. The absolute value is computed from equation (28). According to equation (30) the two curves of diagram E should be identical. The discrepancy between the two curves is probably attributable to statistical errors in the computations and to errors due to a finite number of observations. Diagram F gives the argument $\theta(\omega)$ of the cross-spectrum which according to equation (31) represents the difference of the phase angles of the time series $f_2(t)$ and $f_1(t)$. The phases for high and low frequencies are not plotted because the low power at these frequencies (Diagram D) is considered to be unreliable for use in equation (31) due to statistical errors in computation.

Results of the Application of Linear Operators to Seismic Records

We shall now present figures which describe the results of applying linear operators to ten records of the Magnolia Petroleum Company. The actual mechanics of the method are presented in the previous section. For all the results presented here the form of the operator which was used is given by equation (37), in which the following values of the parameters were taken. The traces were transformed into discrete series, with the time interval h between observations equal to 2.5 milliseconds. The value of M, which represents number of past lags on each trace, was chosen equal to 3. The value of n, which is the number of observations from each trace in the operator time interval, was chosen equal to 50. The value of the prediction distance k, which was allowed to take values of 2, 4, and 6, corresponding to 5 milliseconds, 10 milliseconds, and 15 milliseconds respectively, is given in the figures. The x trace, which is the predicted trace, and the y trace, which is the other trace used in the operator, are marked on the figures.

The values of these parameters were chosen subject to severe limitations in computational facilities. A much more complete analysis of the behavior of the auto- and cross-correlations would be desirable in order to understand better the correct choice of these parameters. Several operators which utilized three traces in their prediction mechanism showed promising results. At the present time further studies are being undertaken on the optimization of these parameters with respect to the analysis of seismic records and the physical characteristics of the phenomenon.

In all the figures which are labeled "Error Curves," the measure of error

was computed from equation (44) with p equal to 10, which means there are 20 squared errors in each average. In Figures 5 through 11 and Figures 13 through 16, the operator time interval is represented by an arrow with the word "Operator" written on it. In these same figures reflections are represented by cross-hatched areas. The cross-hatching runs northeast for reflections which were marked by the Magnolia Petroleum Company, and the cross-hatching runs northwest for reflections which were not marked by the Magnolia Petroleum Company but were determined from company-marked reflection times on corresponding seismic records. In Figures 18 through 21, on the other hand, operator time intervals are represented by cross-hatching, and the reflection times of the first trace are represented by heavy vertical lines.

The four records from Prospect Pace, which we designate as MIT Records Nos. 1, 2, 3, and 4, are shown in Figure 4. These records were taken by a Magnolia Petroleum Company seismic party on March 15, 1950, with A.V.C. traces, filter band F28²-89, and CV phones. Information as to profile, spread, charge, and depth for these records is given in the figures. Table I gives the approximate time durations of reflections marked by the Magnolia Petroleum Company. Time is measured in seconds from the time of the explosion.

TABLE I

REFLECTION TIMES ON RECORDS NO. 1–4

Record	Reflection a (Seconds)	Reflection b (Seconds)	Reflection c (Seconds)	Reflection d (Seconds)
No. 1	.51 to .54	1.00 to 1.04	1.16 to 1.24	Record too short
No. 2	Not marked	Not marked	Not marked	Not marked
No. 3	Not marked	1.00 to 1.04	1.16 to 1.24	1.29 to 1.32
No. 4	Not marked	Not marked	Not marked	Not marked

Figure 5 shows actual and predicted values of trace N750 of MIT Record No. 1. The solid curves in Figure 5 show a section of trace N750 from time equal to .85 seconds to 1.25 seconds. The three dashed curves represent the predicted values of trace N750 for three operators with prediction distances of 5, 10, and 15 milliseconds. In the equation for these operators the x trace was N750 and the y trace was N250. Error Curves for these three operators are shown in Figure 6 (continued) and reduction curves for them are shown in Figure 7. The measure of reduction used in Figure 7 is $1-R_i$, where R_i is given by equation (46).

Figures 6, 8, 9, 10, and 11, give Error Curves for operators taken on MIT Records No. 1, 2, 3, and 4 respectively. For these operators the percent reductions were computed from equation (43) and are given in Table II.

The four records from Prospect T-218, which we designate as MIT Records No. 5, 6, 7, and 8, are shown in Figure 12. These records were taken by a Magnolia Petroleum Company seismic party on March 17, 1950 with A.V.C. traces and filter band F28²-89. Information as to profile, spread, charge, and depth is

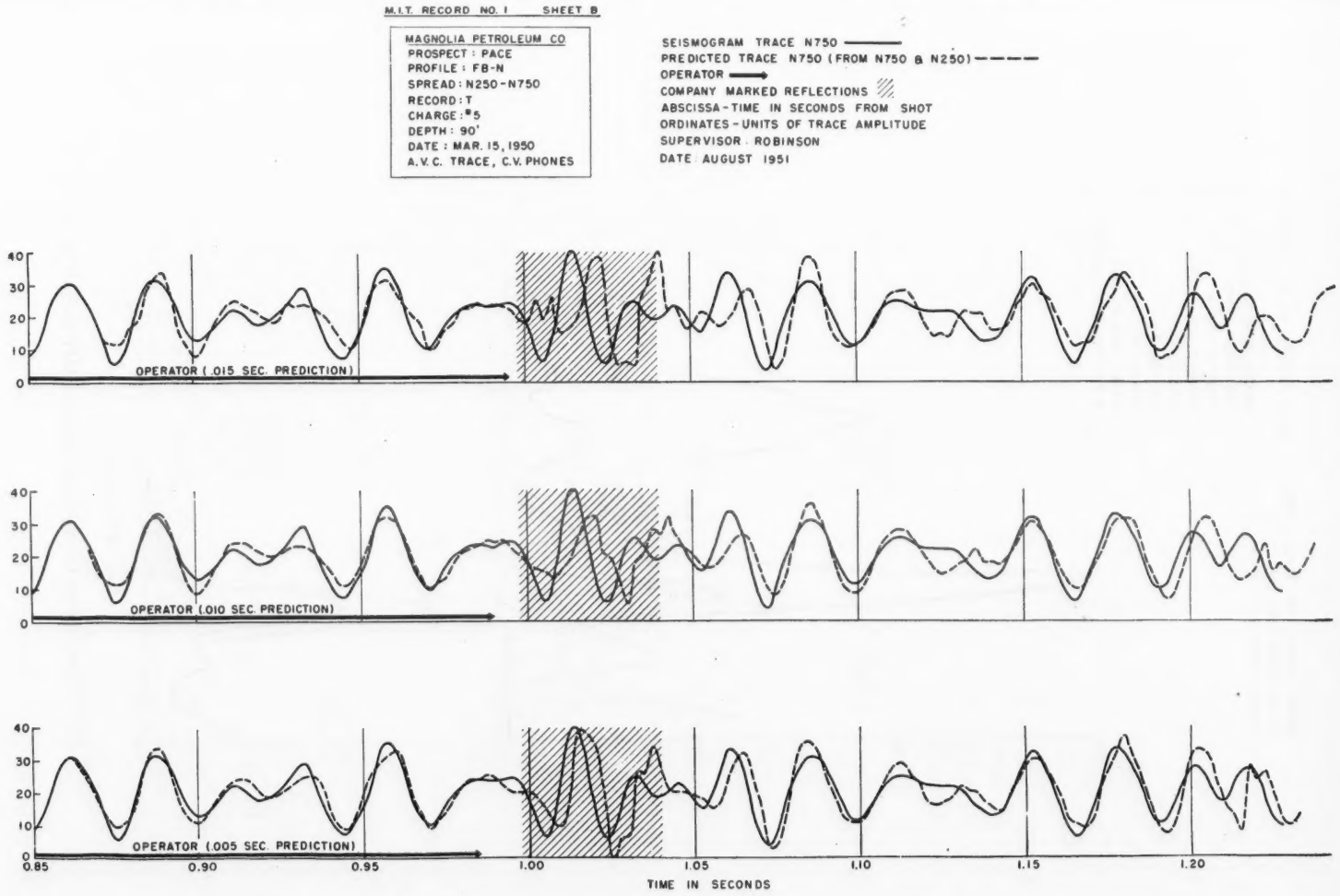

FIG. 5. Actual and predicted values of trace N750, MIT Record No. 1, for operators with various prediction distances.

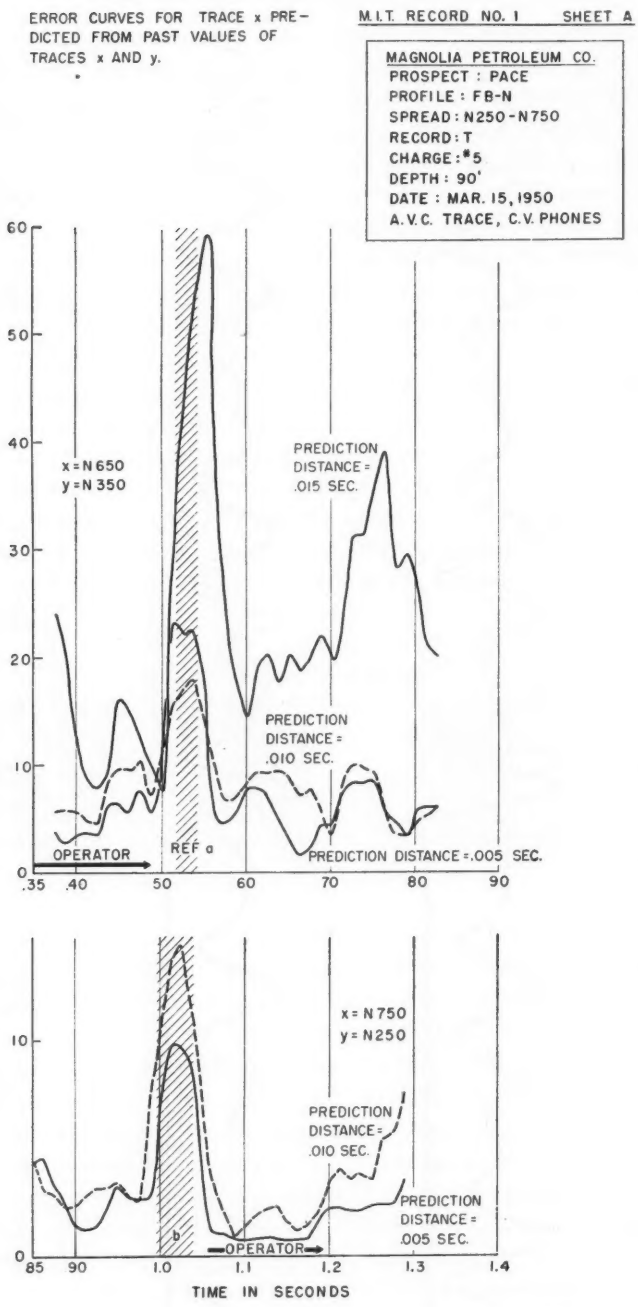

FIG. 6. Error curves for operators taken on MIT Record No. 1.

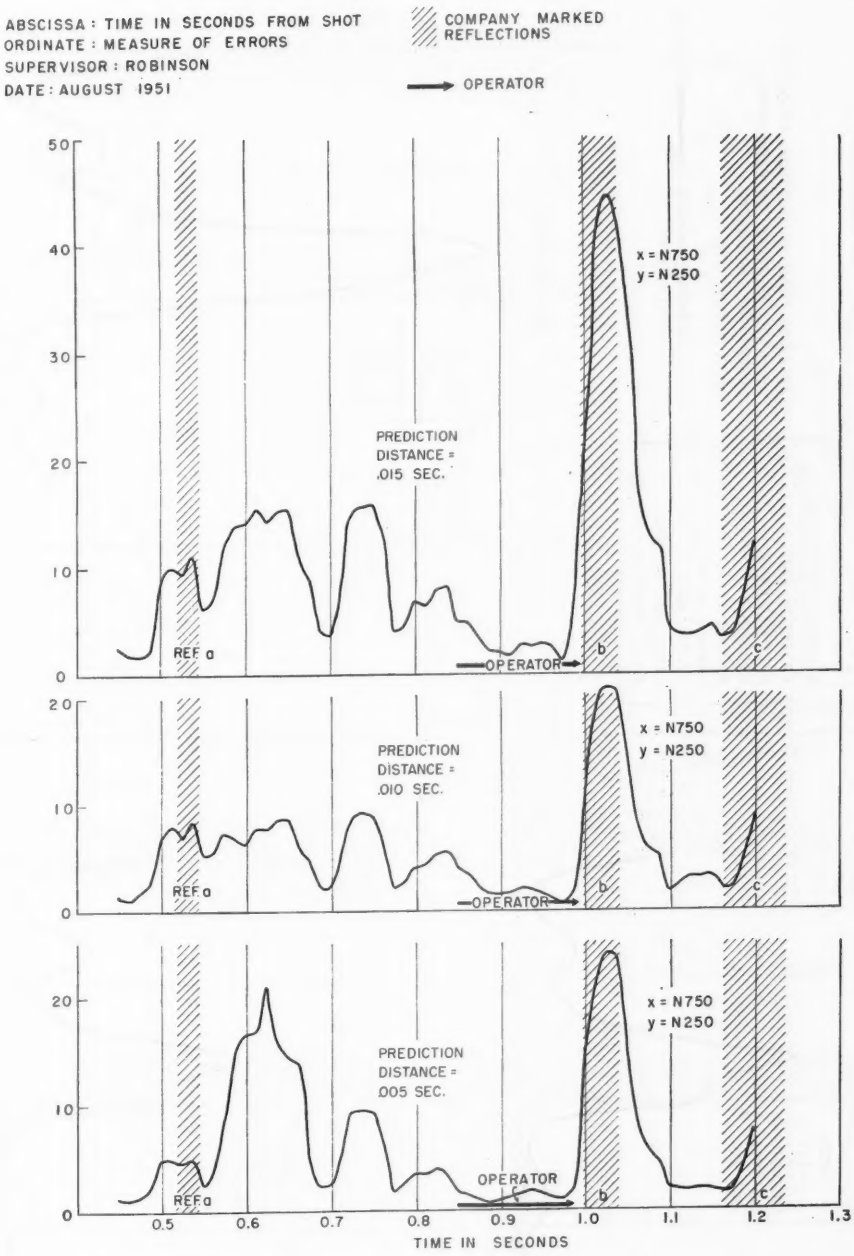

FIG. 6. (Continued). Error curves for operators taken on MIT Record No. 1.

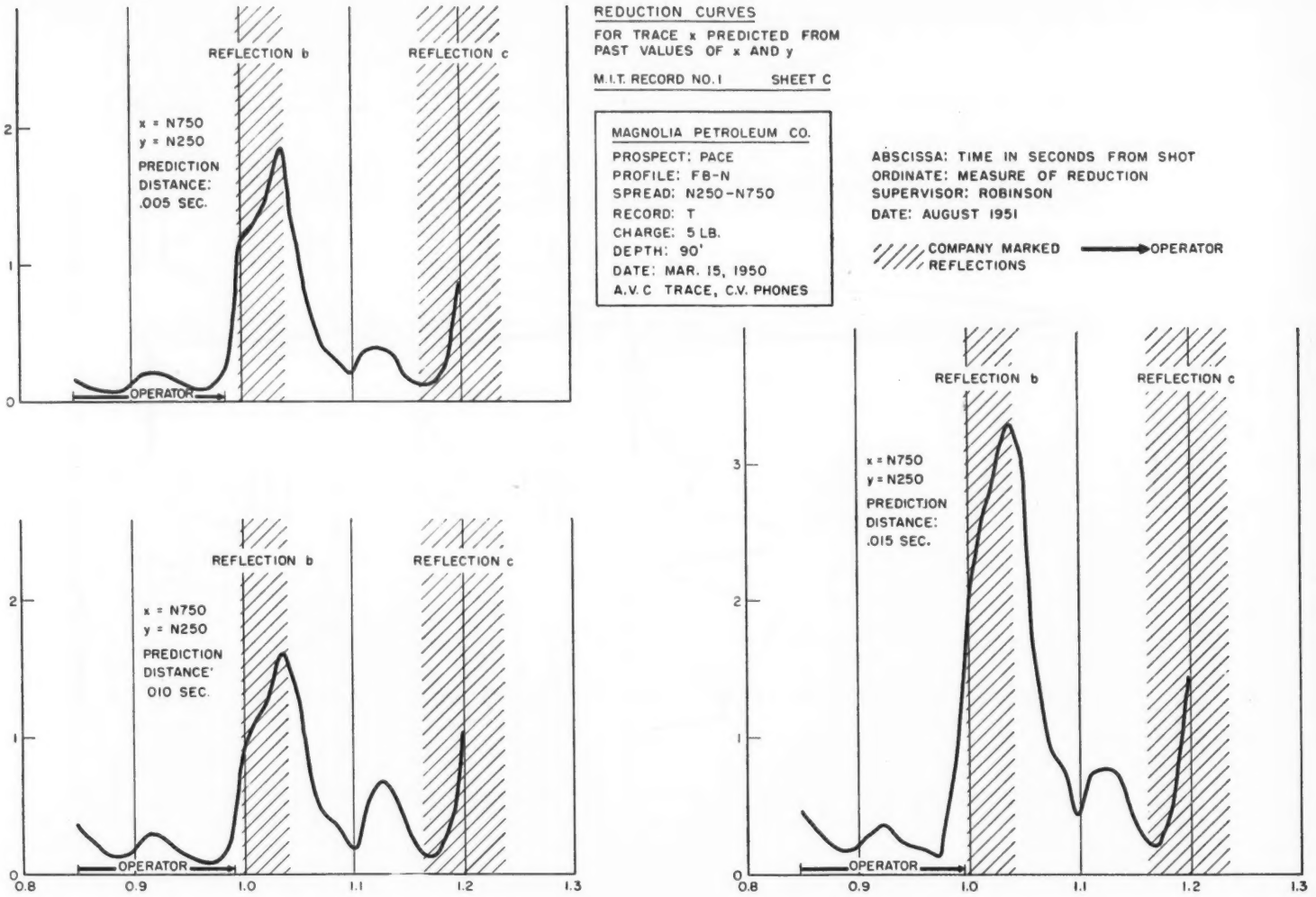

FIG. 7. Reduction curves for operators taken on MIT Record No. 1. (A reduction curve is an error curve from which effects due to variance of trace amplitude have been removed.)

M.I.T. RECORD NO. 2 SHEET A

ERROR CURVES

FIG. 7. Reduction curves for operators taken on MIT Record No. 1. (A reduction curve is an error curve from which effects due to variance of trace amplitude have been removed.)

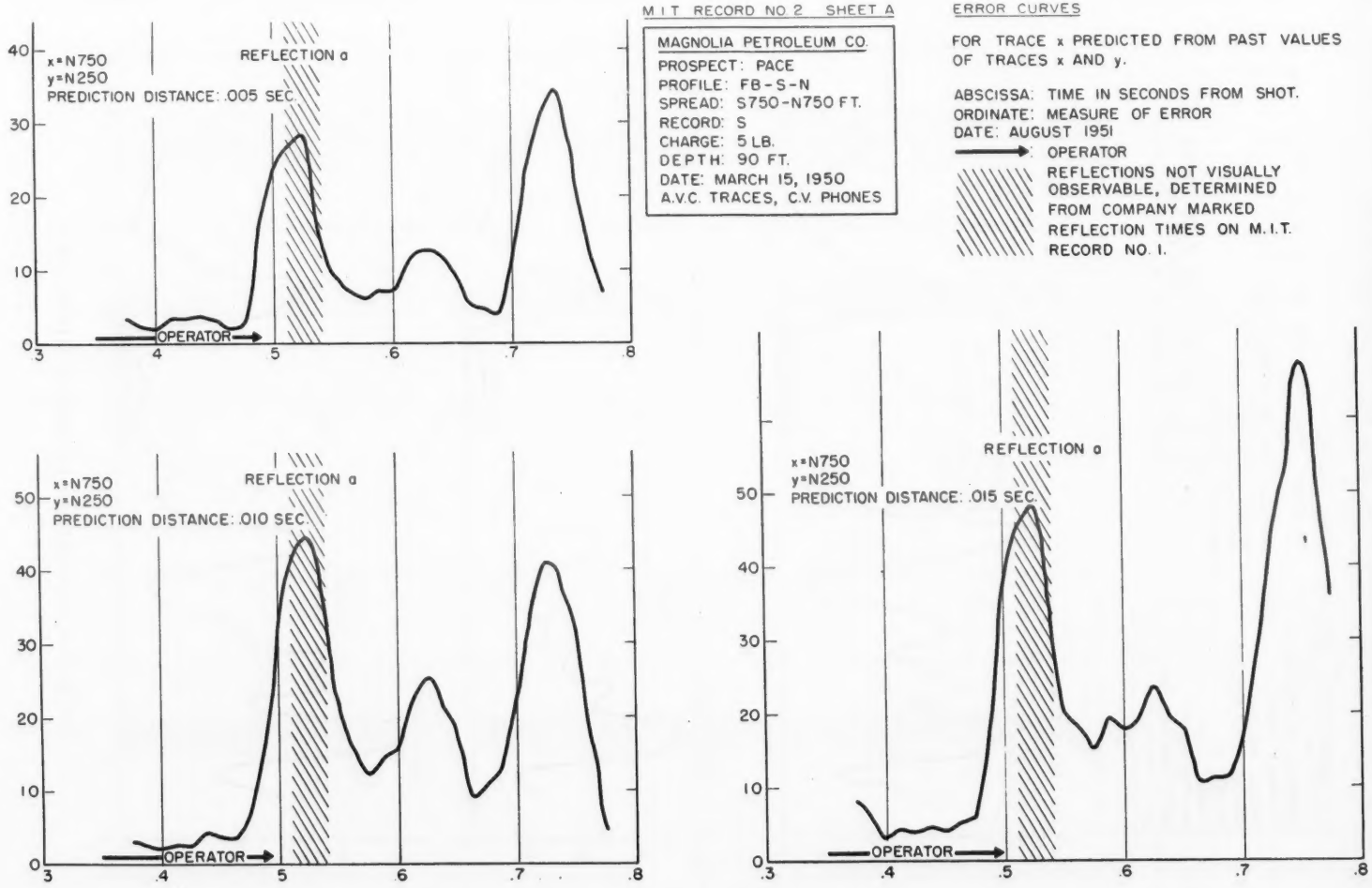

FIG. 8. Error curves for operators taken on MIT Record No. 2.

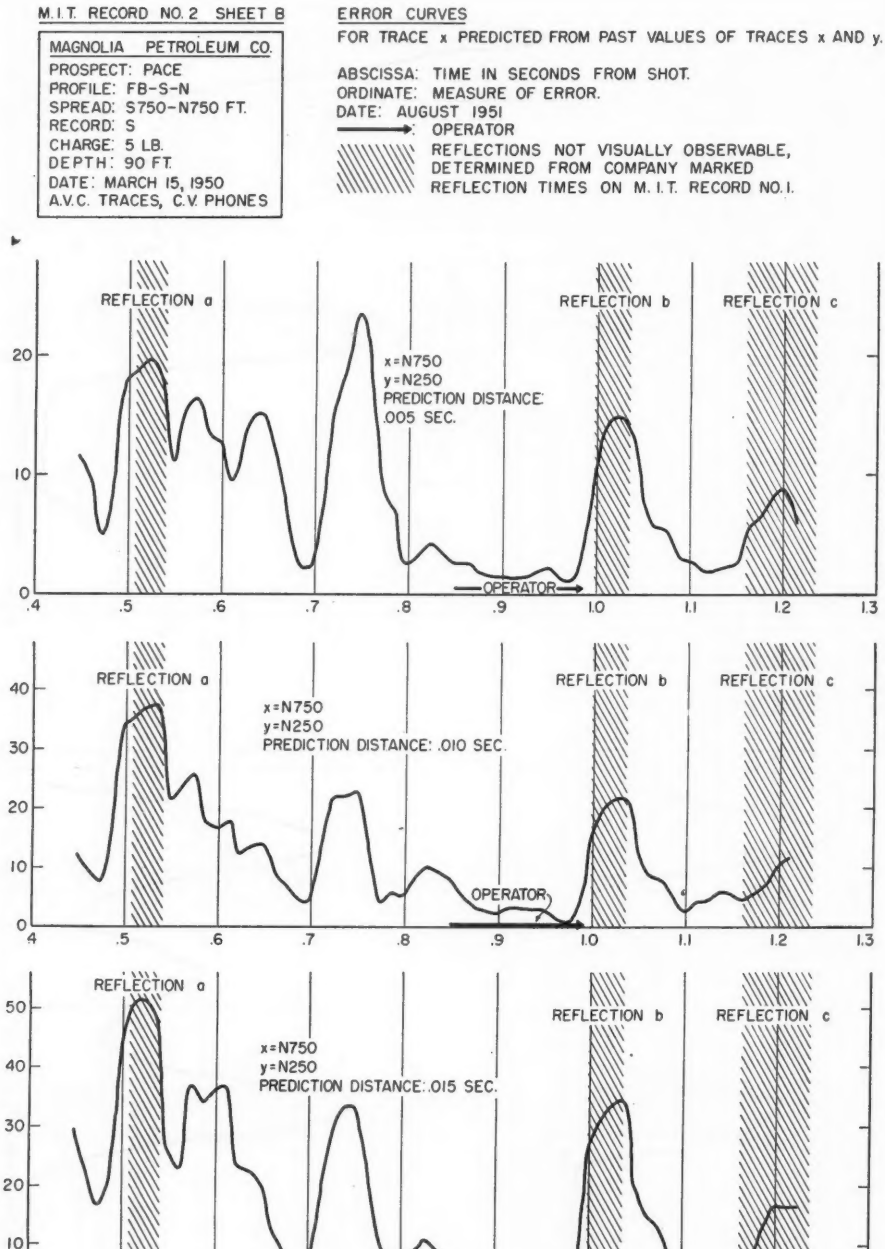

FIG. 9. Error curves for operators taken on MIT Record No. 2.

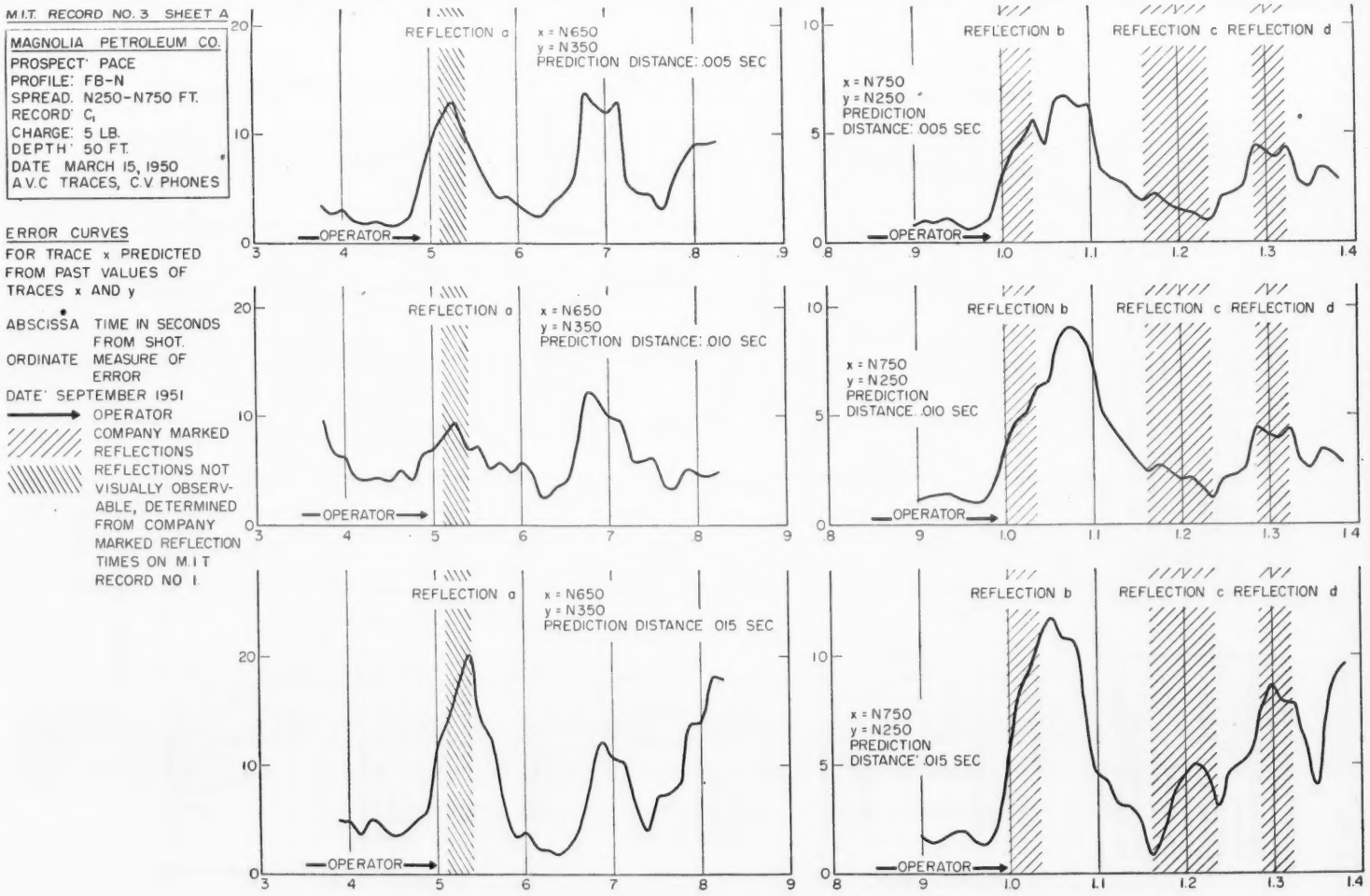

FIG. 10. Error curves for operators taken on MIT Record No. 3.

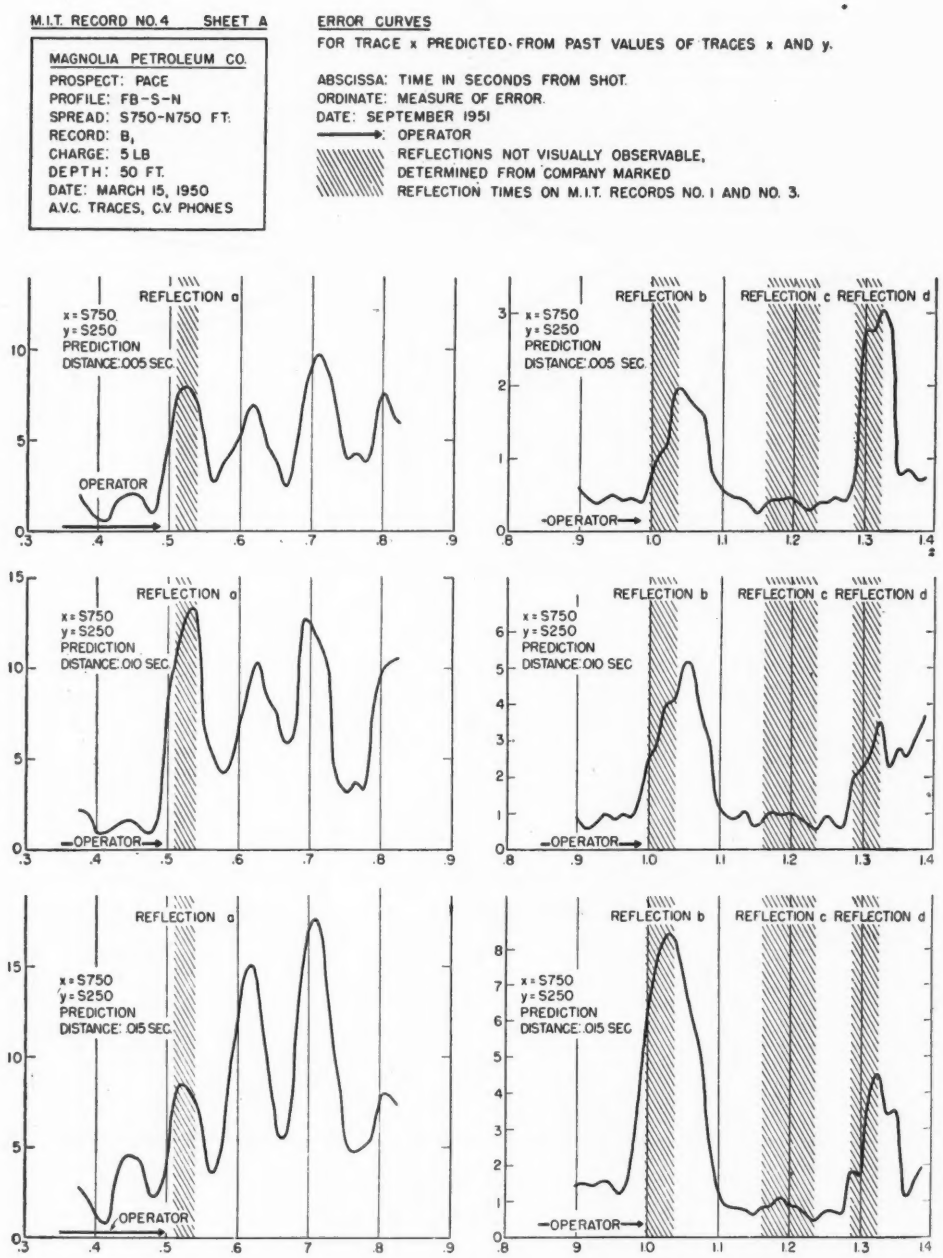

FIG. 11. Error curves for operators taken on MIT Record No. 4.

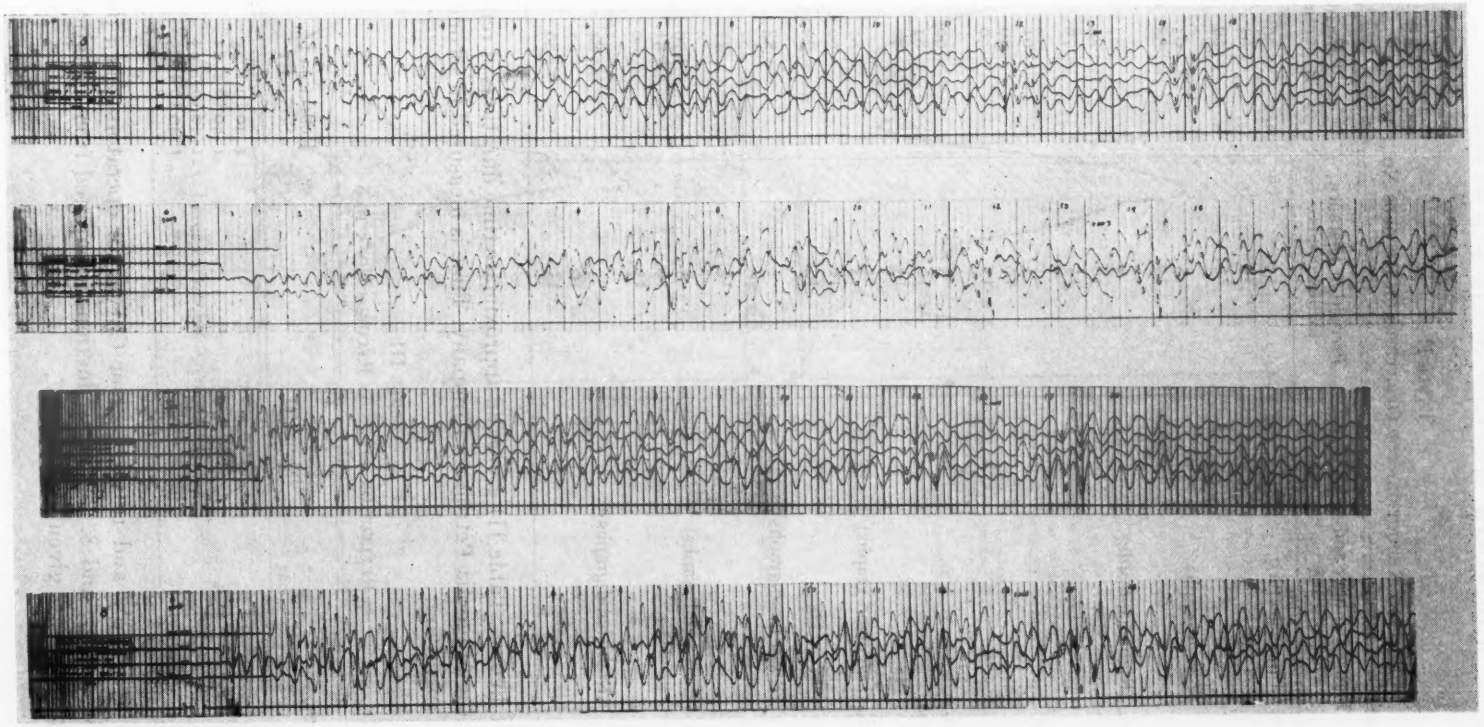

FIG. 12. MIT Records No. 5, 6, 7, and 8. (Furnished by Magnolia Petroleum Co.)

TABLE II

PERCENT REDUCTIONS FOR OPERATORS ON RECORDS NO. 1 TO 4

Figure Number and Description	Prediction Distance (Milliseconds)	Percent Reduction
6. (Upper graph)	5	66
	10	61
	15	59
(Lower graph)	5	93
	10	88
6. (Right-hand side)	5	87
	10	84
	15	78
8.	5	61
	10	49
	15	50
9.	5	90
	10	84
	15	80
10. (Left-hand graphs)	5	82
	10	62
	15	70
(Right-hand graphs)	5	88
	10	87
	15	77
11. (Left-hand graphs)	5	79
	10	83
	15	60
(Right-hand graphs)	5	84
	10	67
	15	80

given in the figures. Table III gives the approximate time durations of reflections marked by the Magnolia Petroleum Company. Time is measured in seconds from the time of explosion.

TABLE III

REFLECTION TIMES ON RECORDS NO. 5 TO 8

Record No.	Reflection e (Seconds)	Reflection f (Seconds)
5	1.17 to 1.23	1.40 to 1.45
6	1.17 to 1.23	1.40 to 1.45
7	1.17 to 1.23	1.40 to 1.45
8	not marked	1.40 to 1.45

Figures 13, 14, 15, and 16 show Error Curves for operators taken on MIT Records No. 5, 6, 7, and 8. Percent reductions, computed from equation (43), for these operators are given in Table IV.

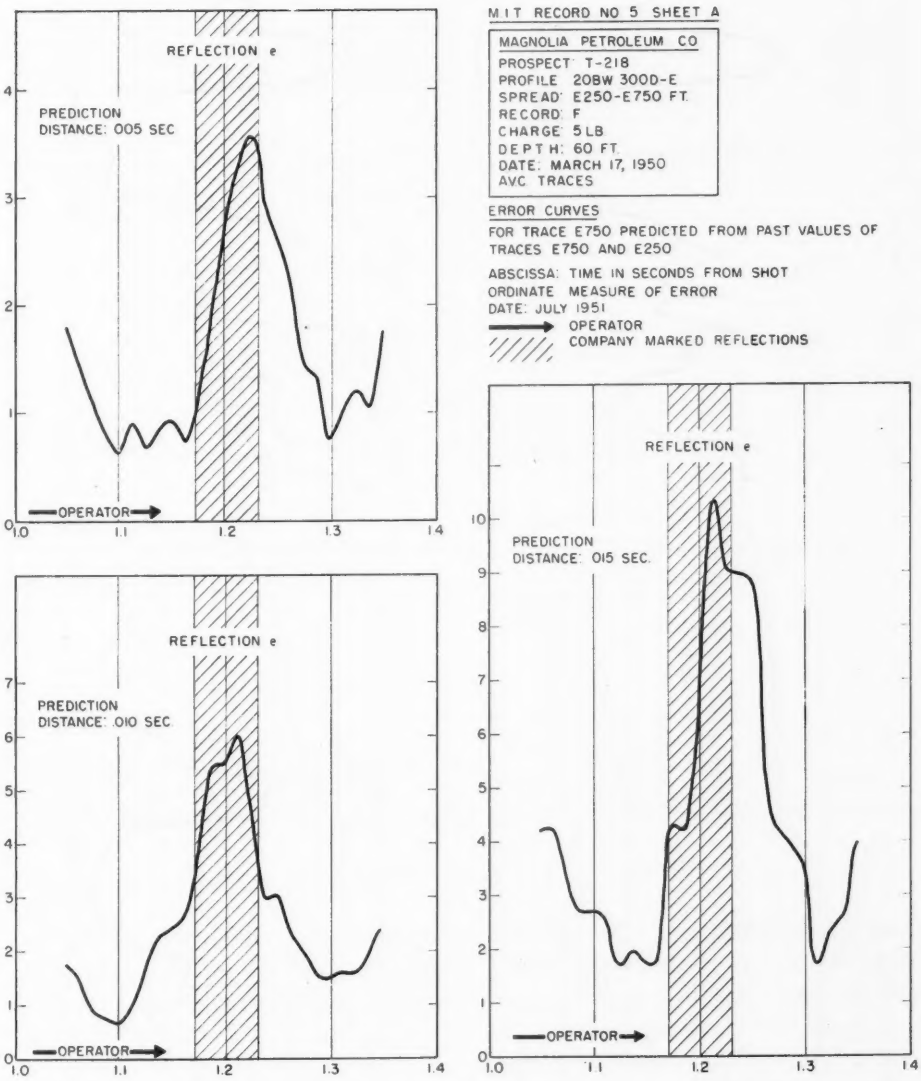

FIG. 13. Error curves for operators taken on MIT Record No. 5.

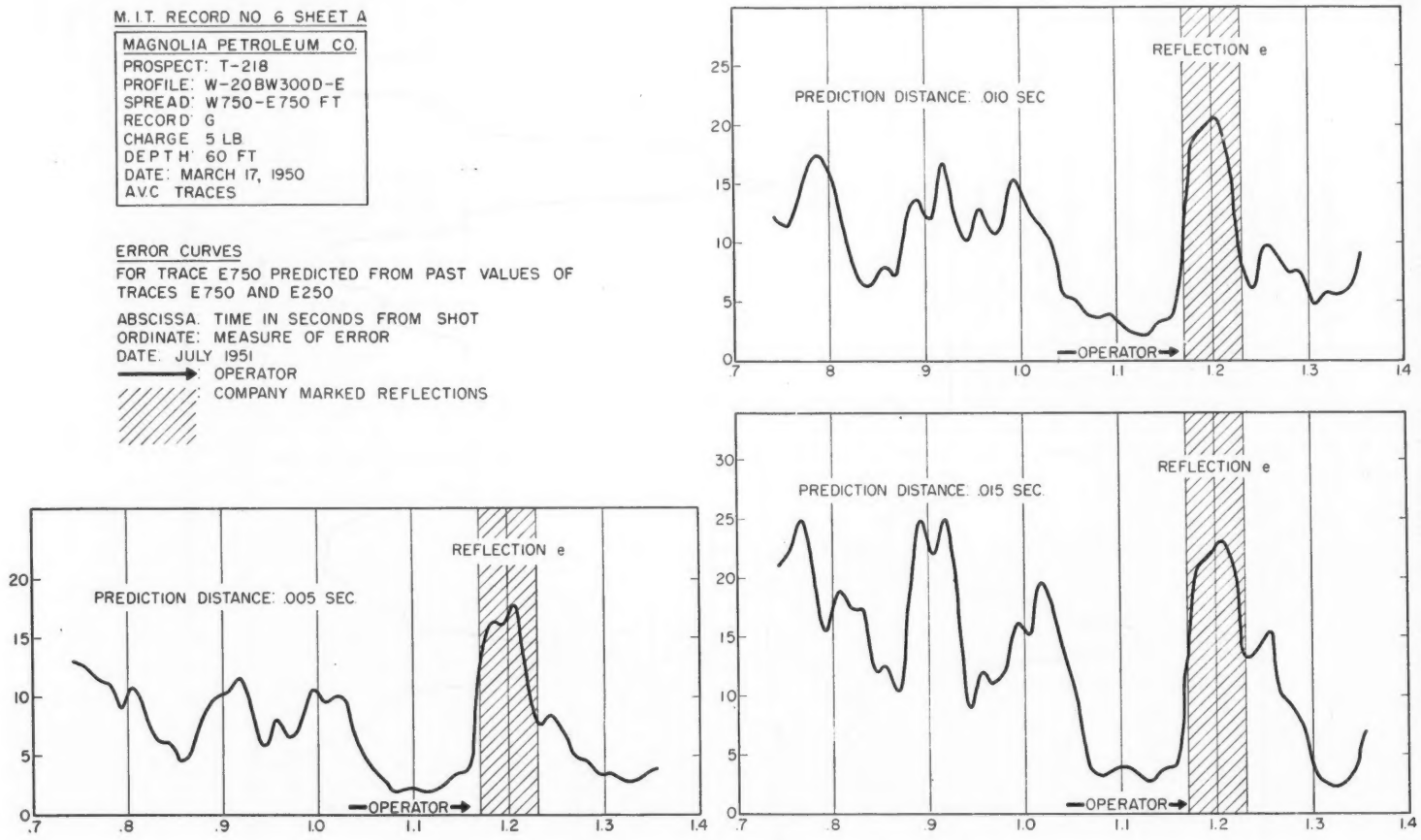

FIG. 14. Error curves for operators taken on MIT Record No. 6.

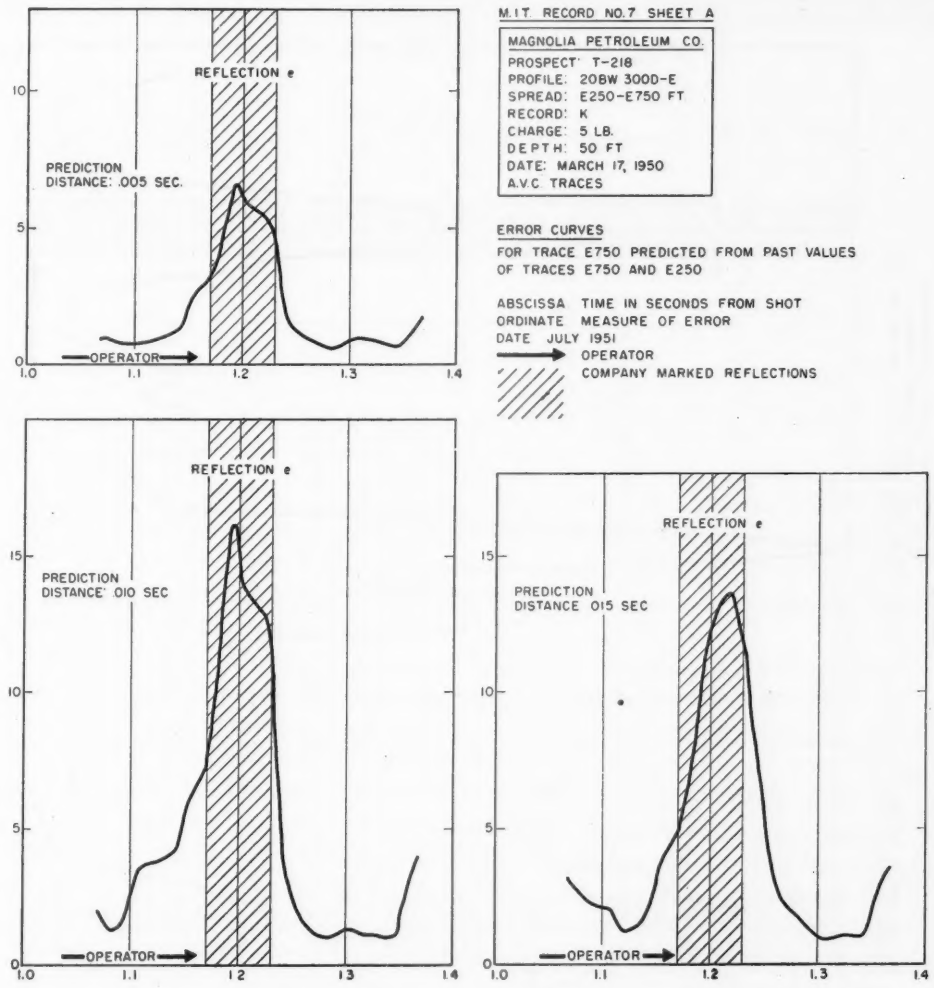

FIG. 15. Error curves for operators taken on MIT Record No. 7.

The percent reductions as shown in Tables II and IV, computed from equation (43), were high for the operators chosen on the records analyzed in comparison with typical percent reductions for operators used in meteorological and economic applications. In spite of the excellent reproduction of the predicted trace in the operator time interval the prediction errors in this interval were highly autocorrelated. Therefore, even better reproductions of the predicted trace can be expected by using more traces and more lags on these traces in the form of the operator. For the errors presented in the figures, our tentative judgment is that the magnitude of errors at reflections are in most cases significantly different from the magnitude of errors in non-reflection intervals. Any statistical test of

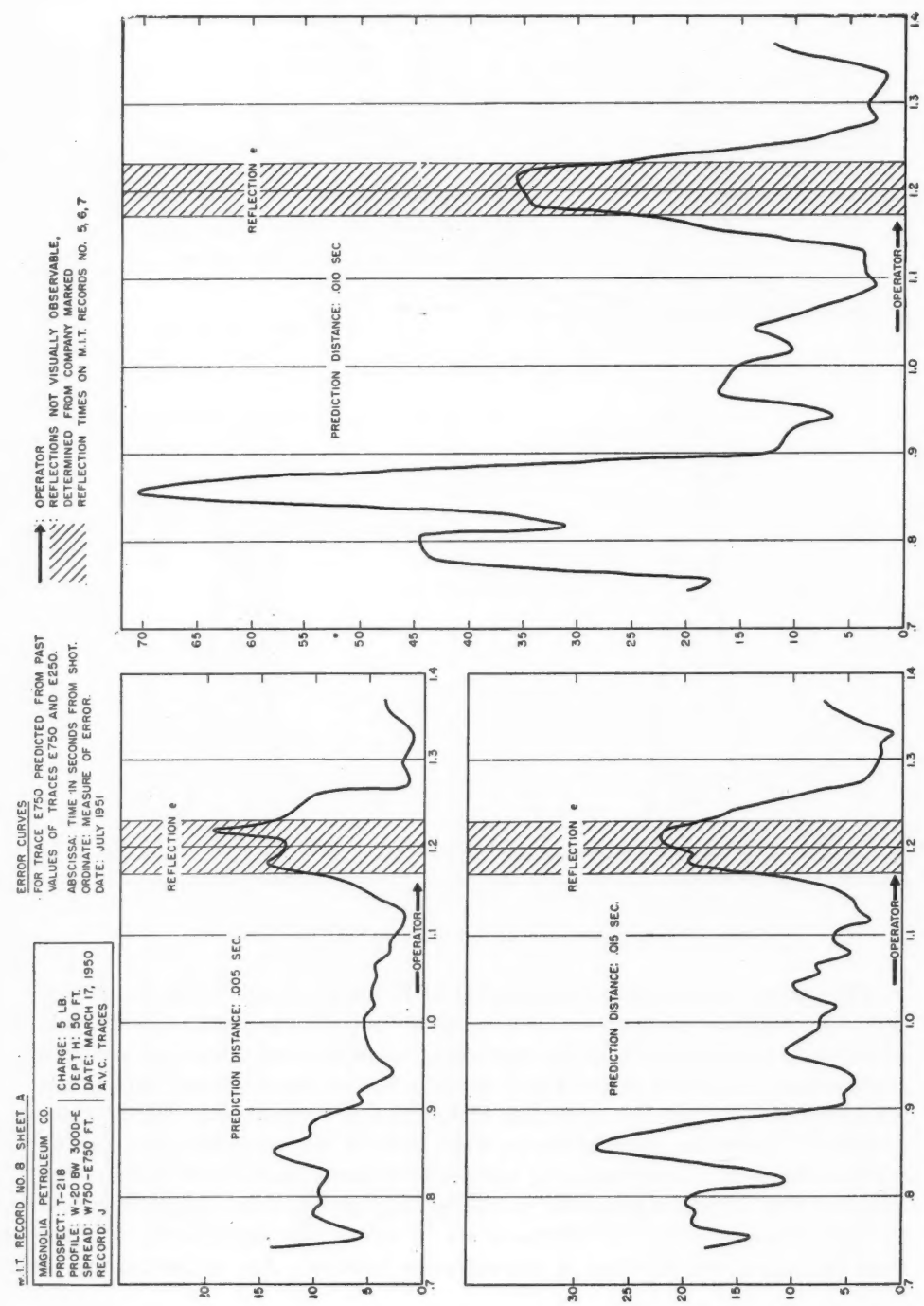
M.I.T. RECORD NO. 8 SHEET A
MAGNOLIA PETROLEUM CO.
PROSPECT: T-218
PROFILE: W-20 BW 3000-E
SPREAD: W750-E750 FT.
RECORD: J
CHARGE: 5 LB
DEPTH: 50 FT.
DATE: MARCH 17, 1950
A.V.C. TRACES
ERROR CURVES
FOR TRACE E750 PREDICTED FROM PAST VALUES OF TRACES E750 AND E250.
ABSCISSA: TIME IN SECONDS FROM SHOT.
ORDINATE: MEASURE OF ERROR.
DATE: JULY 1951
OPERATOR
REFLECTIONS NOT VISUALLY OBSERVABLE, DETERMINED FROM COMPANY MARKED REFLECTION TIMES ON M.I.T. RECORDS NO. 5, 6, 7
PREDICTION DISTANCE: .005 SEC.
PREDICTION DISTANCE: .010 SEC
PREDICTION DISTANCE: .015 SEC.
REFLECTION e
OPERATOR

FIG. 16. Error curves for operators taken on MIT Record No. 8.

TABLE IV

PERCENT REDUCTIONS FOR OPERATORS ON RECORDS NO. 5–8

Figure No.	Prediction Distance (Milliseconds)	Percent Reduction
13	5	82
	10	82
	15	66
14	5	87
	10	83
	15	82
15	5	90
	10	81
	15	81
16	5	93
	10	85
	15	85

significance which might be used must take into account the autocorrelation of errors, and hence the usual chi-square test of significance is invalid. The whole problem of tests of significance, tests of hypotheses, and other questions regarding estimation is now under investigation.

The Magnolia Petroleum Company Record H from prospect 4-E was shot on the Forehand Farm in Henderson County, Texas, where about sixty feet of loose Carrizo sand is underlain by Wilcox sandy clay with lignite stringers. The record is shown in Figure 17. The Magnolia Petroleum Company considers this to be a problem area because of the loose sand. The spread is rather far from the shot, as indicated on the record. This causes early reflections to have appreciable "step-out" because of the non-vertical path. Reflection times on the top trace are marked by ϕ, and times on lower traces are later, depending on the amount of departure from vertical travel. A different shooting procedure showed these reflections much better and provided the basis for indicating reflection times. Figures 18 and 19 give Error Curves for operators taken on Record H from Prospect 4-E. The heavy vertical lines indicate the reflection times of the top trace, which are marked by ϕ. In the equation for the operator the x trace, which is the predicted trace, was trace 4, and the y trace was trace 1.

The Magnolia Petroleum Company Record K (profile 65 A-W-1) and Record K (profile 65 A-W-2) (Figure 17) were prepared from an original shot in West Texas where high-speed materials are near the surface. On Record K (profile 65 A-W-1) the top six traces represent a relatively wide band recording and the bottom six represent the same stations with proper measures taken to develop reflections. The first four traces of Record K (profile 65 A-W-1) are reproduced at higher amplitudes on Record K (profile 65 A-W-2). Figures 20 and 21 give Error Curves for operators taken on Record K (profile 65 A-W-2). In the equation for the operator the x trace, which is the predicted trace, was trace 4 and the y trace was trace 1.

FIG. 16. Error curves for operators taken on MIT Record No. 8.

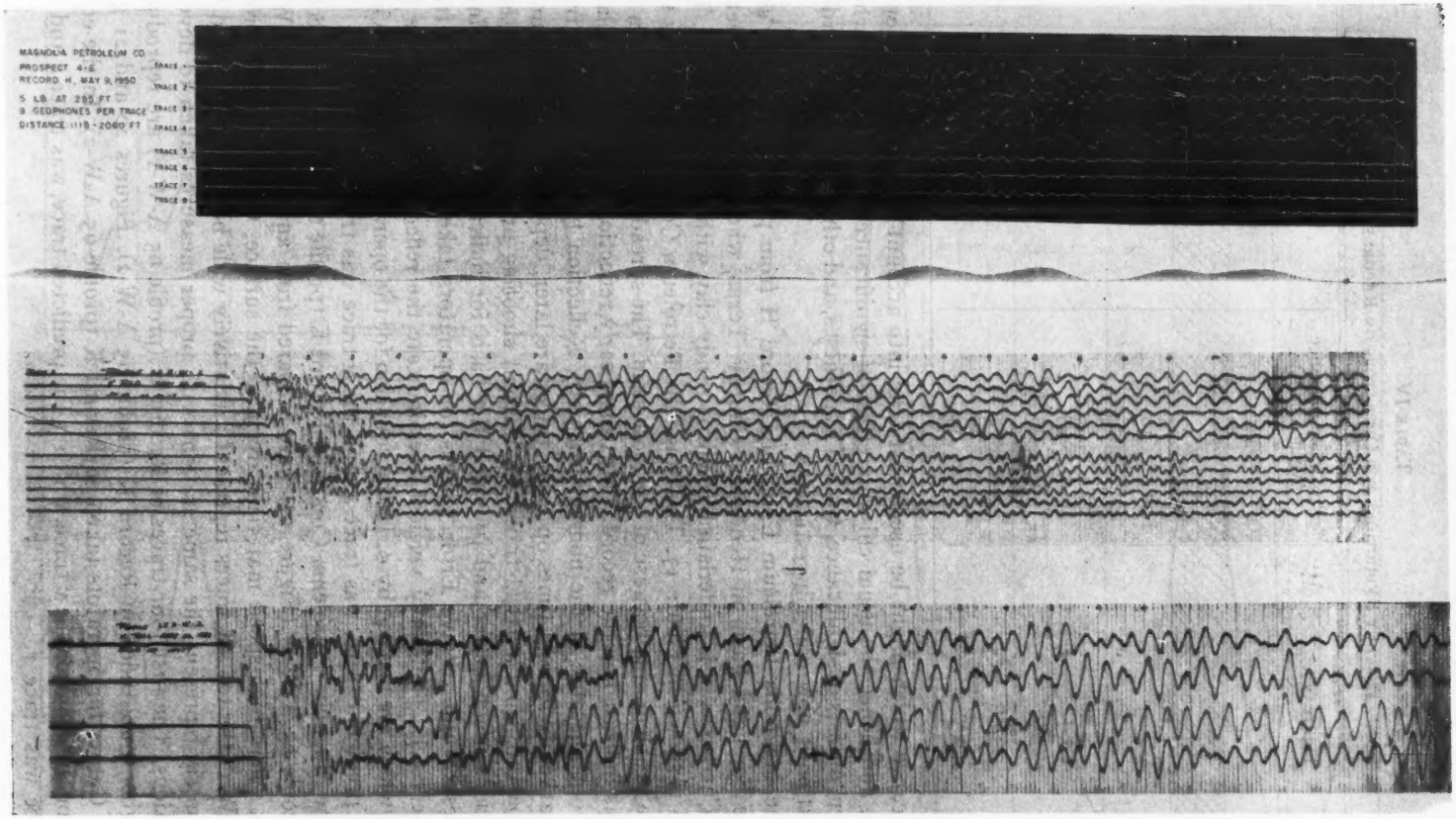

FIG. 17. Record H (prospect 4-E), Record K (profile 65 A-W-1), and Record K (profile 65 A-W-2). (Furnished by Magnolia Petroleum Co.)

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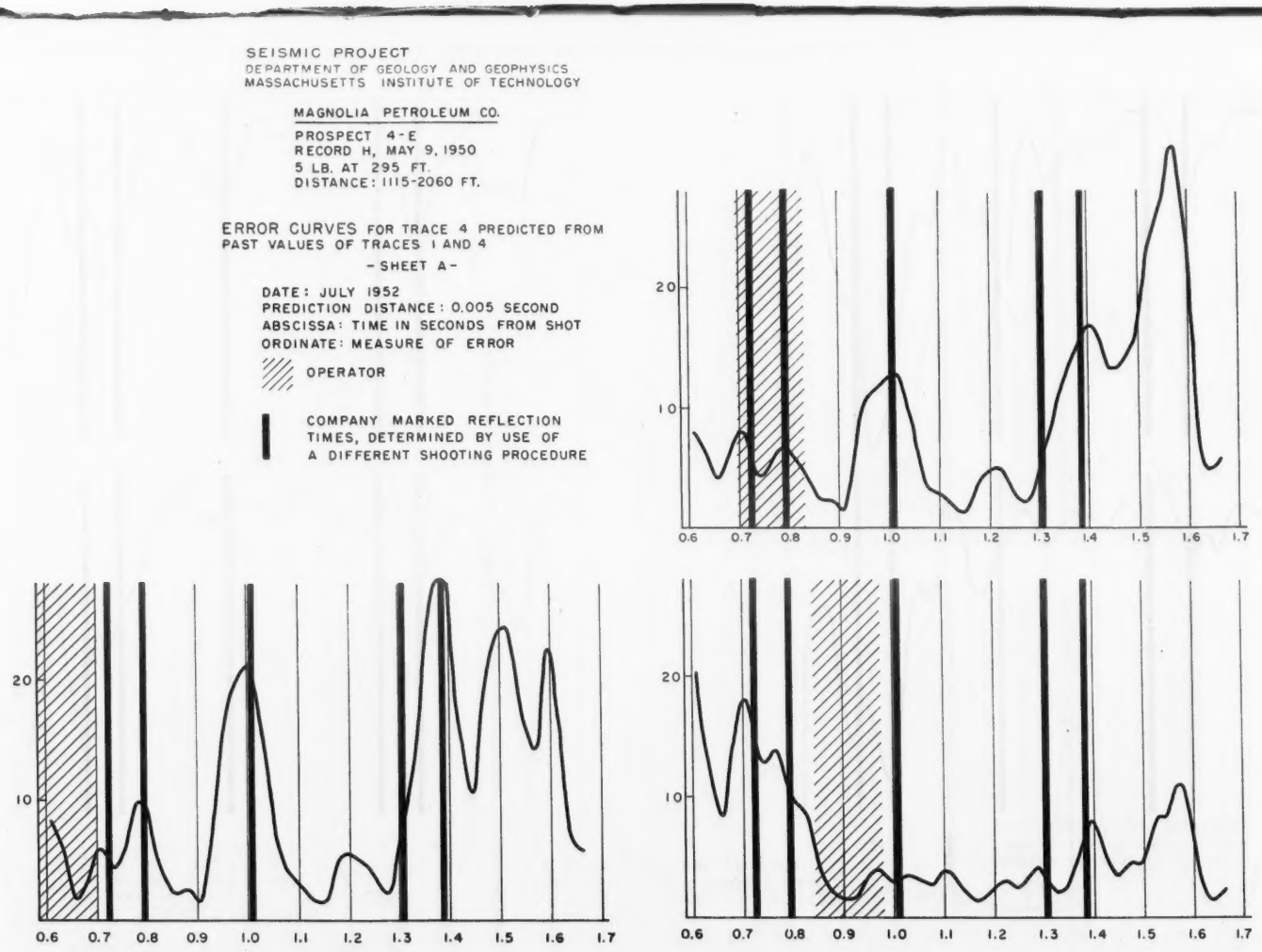
SEISMIC PROJECT
DEPARTMENT OF GEOLOGY AND GEOPHYSICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MAGNOLIA PETROLEUM CO.
PROSPECT 4-E
RECORD H, MAY 9, 1950
5 LB. AT 295 FT.
DISTANCE: 1115-2060 FT.
ERROR CURVES FOR TRACE 4 PREDICTED FROM PAST VALUES OF TRACES 1 AND 4
- SHEET A -
DATE: JULY 1952
PREDICTION DISTANCE: 0.005 SECOND
ABSCISSA: TIME IN SECONDS FROM SHOT
ORDINATE: MEASURE OF ERROR
OPERATOR
COMPANY MARKED REFLECTION TIMES, DETERMINED BY USE OF A DIFFERENT SHOOTING PROCEDURE
20
10
0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7

FIG. 18. Error curves for operators taken on Record H (prospect 4-E).

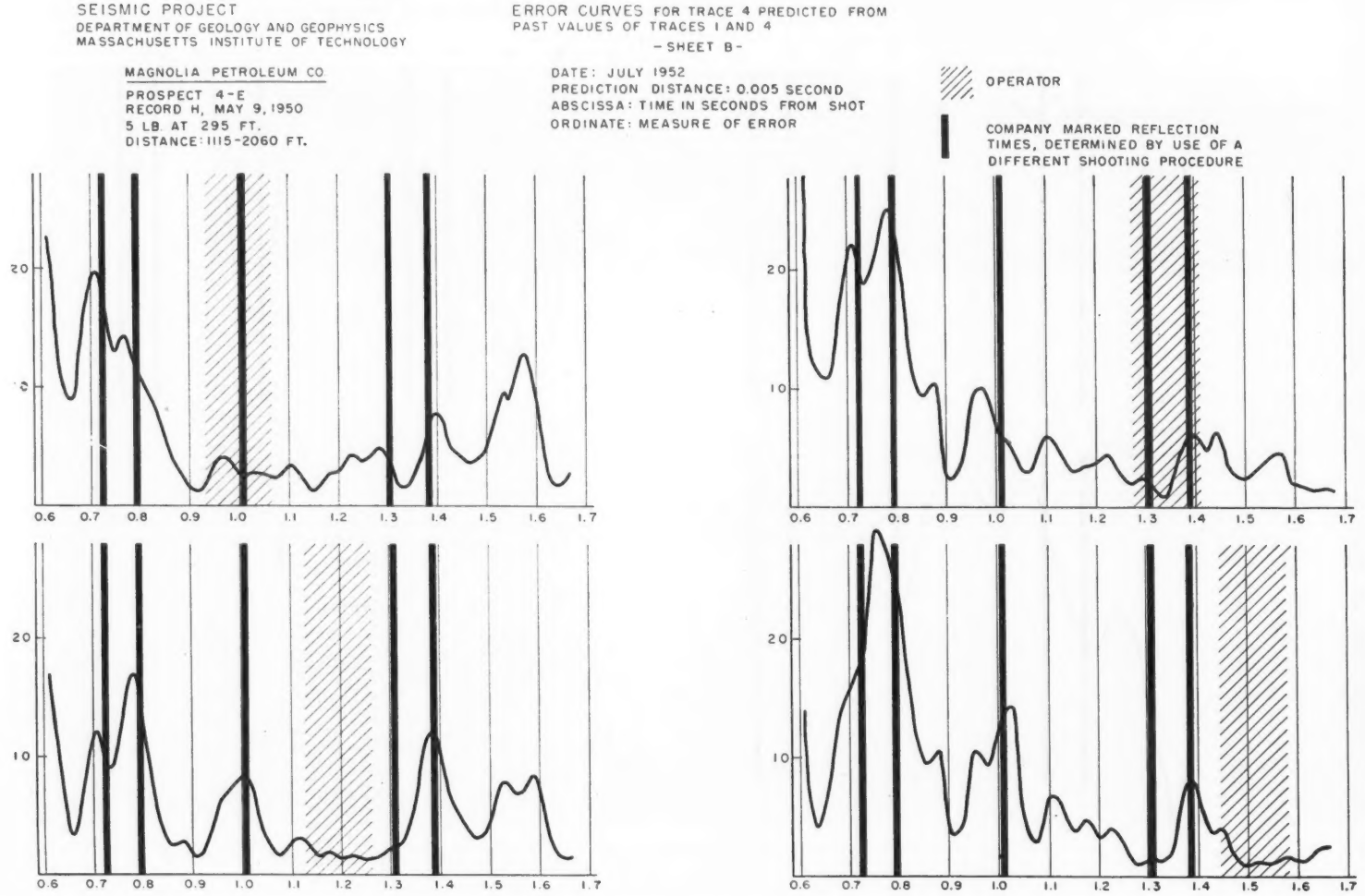
SEISMIC PROJECT
DEPARTMENT OF GEOLOGY AND GEOPHYSICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MAGNOLIA PETROLEUM CO.
PROSPECT 4-E
RECORD H, MAY 9, 1950
5 LB. AT 295 FT.
DISTANCE: 1115-2060 FT.
ERROR CURVES FOR TRACE 4 PREDICTED FROM PAST VALUES OF TRACES 1 AND 4
- SHEET B -
DATE: JULY 1952
PREDICTION DISTANCE: 0.005 SECOND
ABSCISSA: TIME IN SECONDS FROM SHOT
ORDINATE: MEASURE OF ERROR
OPERATOR
COMPANY MARKED REFLECTION TIMES, DETERMINED BY USE OF A DIFFERENT SHOOTING PROCEDURE
20
0
10
0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7

FIG. 19. Error curves for operators taken on Record H (prospect 4-E).

SEISMIC PROJECT
DEPARTMENT OF GEOLOGY AND GEOPHYSICS
ERROR CURVES FOR TRACE 4 PREDICTED FROM PAST VALUES OF TRACES 1 AND 4
10

FIG. 19. Error curves for operators taken on Record H (prospect 4-E).

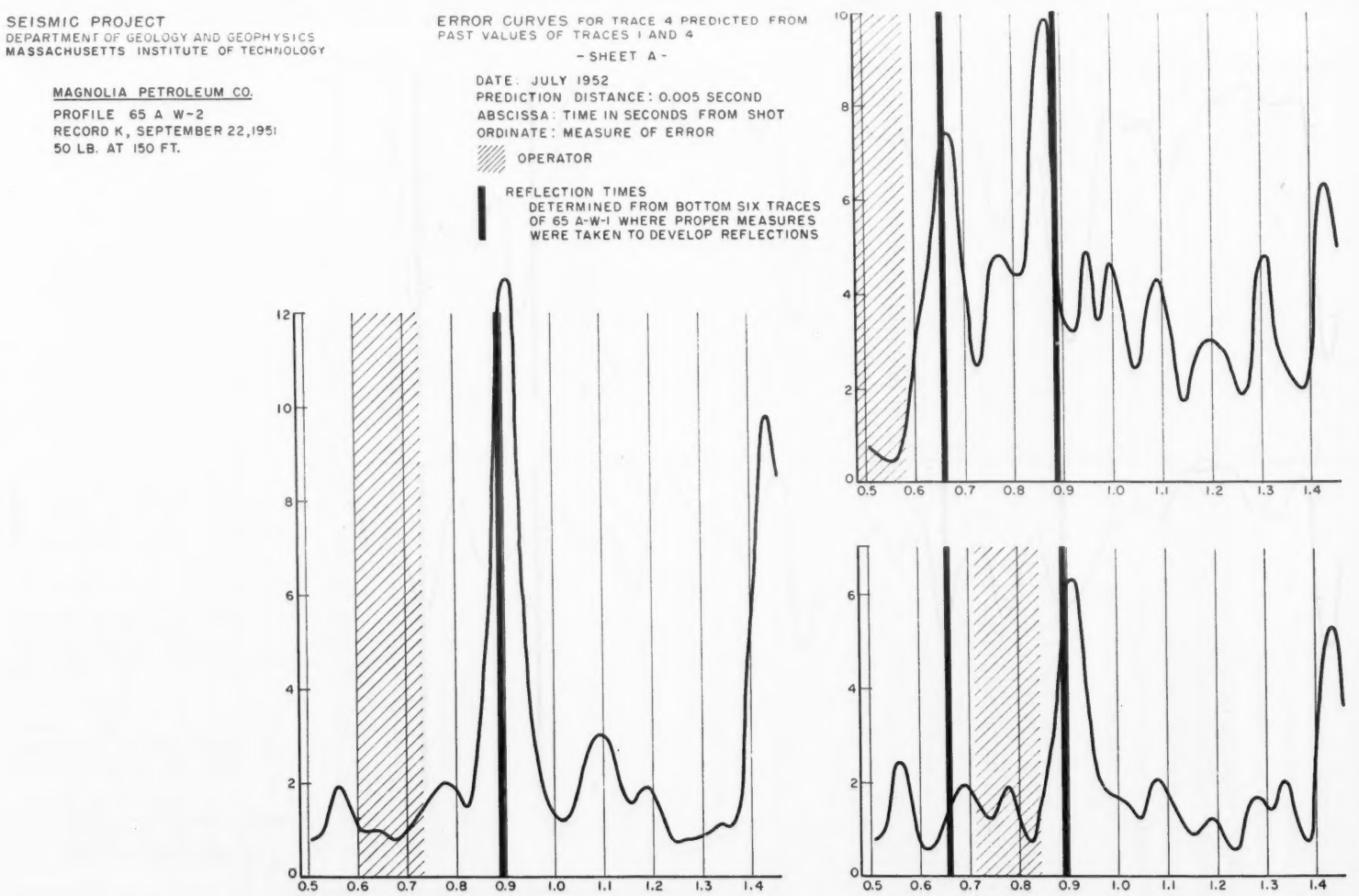
SEISMIC PROJECT
DEPARTMENT OF GEOLOGY AND GEOPHYSICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MAGNOLIA PETROLEUM CO.
PROFILE 65 A W-2
RECORD K, SEPTEMBER 22,1951
50 LB. AT 150 FT.
ERROR CURVES FOR TRACE 4 PREDICTED FROM PAST VALUES OF TRACES 1 AND 4
- SHEET A -
DATE: JULY 1952
PREDICTION DISTANCE: 0.005 SECOND
ABSCISSA: TIME IN SECONDS FROM SHOT
ORDINATE: MEASURE OF ERROR
OPERATOR
REFLECTION TIMES DETERMINED FROM BOTTOM SIX TRACES OF 65 A-W-1 WHERE PROPER MEASURES WERE TAKEN TO DEVELOP REFLECTIONS
0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4

FIG. 20. Error curves for operators taken on Record K (profile 65 A-W-2).

SEISMIC PROJECT
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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MAGNOLIA PETROLEUM CO.
PROFILE 65 A W-2
RECORD K, SEPTEMBER 22, 1951
50 LB. AT 150 FT.

ERROR CURVES FOR TRACE 4
PREDICTED FROM PAST VALUES OF
TRACES 1 AND 4
-SHEET 8-

DATE: JULY 1952
PREDICTION DISTANCE: 0.005 SECOND
ABSCISSA: TIME IN SECONDS
FROM SHOT
ORDINATE: MEASURE OF ERROR

OPERATOR

REFLECTION TIMES
DETERMINED FROM BOTTOM SIX
TRACES OF 65 A-W-1 WHERE
PROPER MEASURES WERE TAKEN
TO DEVELOP REFLECTIONS

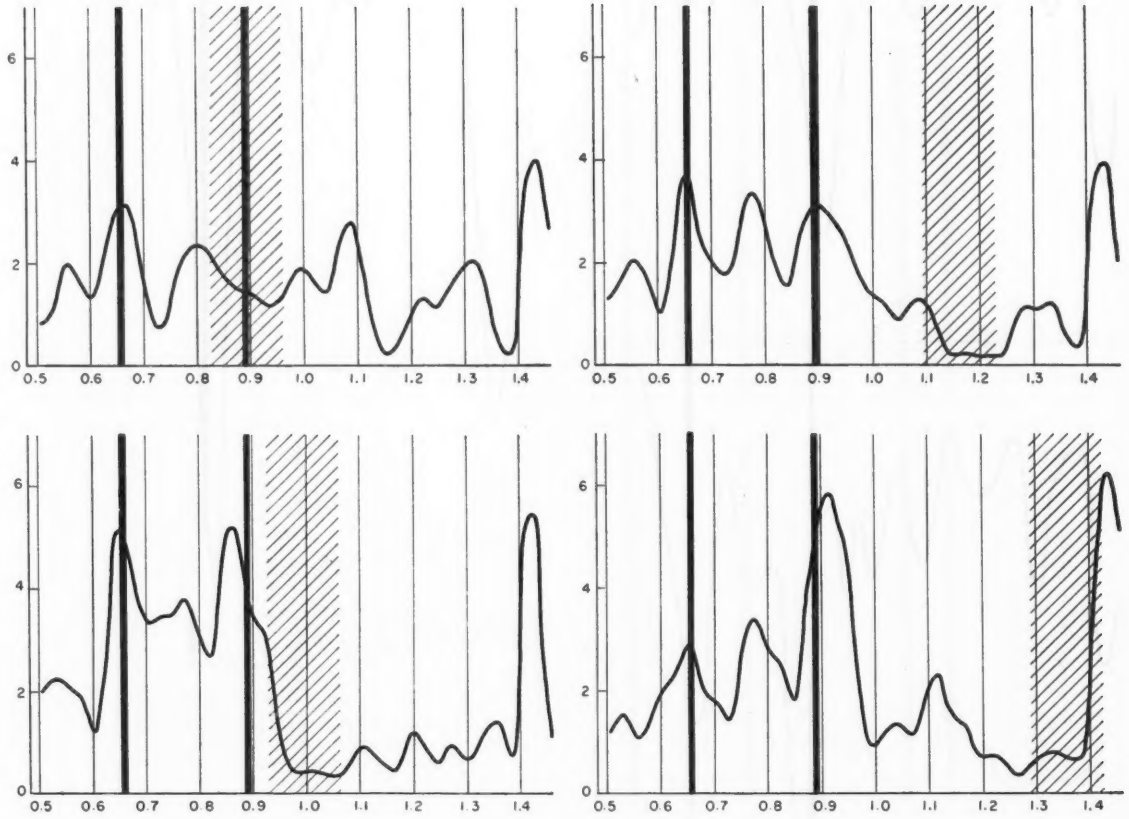

FIG. 21. Error curves for operators taken on Record K (profile 65 A-W-2).

All the computations on MIT Records No. 1 through 8 were done by girls utilizing desk calculators. In the derivation of the Error Curves for Record H (prospect 4-E) and Record K (profile 65 A-W-2) the cross products involved in the set of simultaneous equations (40), and the measure of error given by equation (44), were computed on the MIT Whirlwind Digital Computer. Nevertheless, the solutions of the sets of simultaneous equations (40) for the operator coefficients were computed with desk calculators. The Crout method for solving systems of linear simultaneous equations (Ref. 9) was used throughout the computational work.

The large scale applications of statistical methods to seismology in order to find general use require rapid, automatic, and relatively cheap computational methods. The type of computing machinery most applicable is the general purpose high-speed electronic digital computer, although several special purpose computers may serve the purpose equally as well. Magnetic tape seismogram recordings used in conjunction with digital-to-analog converters would make it possible to transfer the seismic data directly to the computing machines.

APPENDIX

As in the section on Time Series, we let $f_1(t)$ and $f_2(t)$ represent stationary time series. Then by letting $f_{1T}(t)=f_1(t)$ for $-T<t<T$ and $f_{1T}=0$ elsewhere Y. W. Lee (Ref. 8) defines the complex amplitude and phase spectrum as

$$F_{1T}(\omega) = \frac{1}{2\pi}\int_{-T}^{T} f_{1T}(t)e^{-i\omega t}dt. \tag{59}$$

He defines the power density spectrum as

$$\Phi_{11}(\omega) = \lim_{T\to\infty} \frac{\pi}{T}\left| F_{1T}(\omega)\right|^2. \tag{60}$$

From this definition he shows that equations (8) and (9), which are the equations we used to define the power density spectrum, hold. In a similar manner he defines the cross power density spectrum as

$$\Phi_{12}(\omega) = \lim_{T\to\infty}\left[\frac{\pi}{T}F_{1T}(\omega)\overline{F_{2T}(\omega)}\right] \tag{61}$$

where the bar indicates the complex conjugate. From this definition, equations (23) and (24), which were used to define the cross spectrum follow as theorems.

Using these definitions of Y. W. Lee, we shall derive equations (30) and (31) in an heuristic manner. Using the theorem that the products of two limits which exist is equal to the limit of the products, we have

$$\Phi_{11}(\omega)\Phi_{22}(\omega) = \lim_{T\to\infty}\frac{\pi^2}{T^2}\left| F_{1T}(\omega)\right|^2\left| F_{2T}(\omega)\right|^2. \tag{62}$$

FIG. 21. Error curves for operators taken on Record K (profile 65 A-W-2).

By taking the positive square roots of this expression it becomes

$$\sqrt{\Phi_{11}(\omega)}\,\sqrt{\Phi_{22}(\omega)} = \lim_{T\to\infty} \frac{\pi}{T} \left| F_{1T}(\omega) \right| \left| F_{2T}(\omega) \right|. \tag{63}$$

By writing the complex amplitude and phase spectra as

$$F_{1T}(\omega) = \left| F_{1T}(\omega) \right| e^{i\theta_{1T}(\omega)} \tag{64}$$

and similarly for $F_{2T}(\omega)$, we see that the cross power spectrum, given by definition (61), is

$$\Phi_{12}(\omega) = \lim_{T\to\infty} \left[\frac{\pi}{T} \left| F_{1T}(\omega) \right| \left| F_{2T}(\omega) \right| e^{i[\theta_{1T}(\omega)-\theta_{2T}(\omega)]} \right]. \tag{65}$$

If we assume that the limits

$$\theta_1(\omega) = \lim_{T\to\infty} \theta_{1T}(\omega) \quad \text{and} \quad \theta_2(\omega) = \lim_{T\to\infty} \theta_{2T}(\omega) \tag{66}$$

exist, then by using equation (63), we have

$$\Phi_{12}(\omega) = \sqrt{\Phi_{11}(\omega)}\,\sqrt{\Phi_{22}(\omega)}\, e^{i[\theta_1(\omega)-\theta_2(\omega)]}. \tag{67}$$

From this equation we see that the absolute value of the cross-spectrum is given by equation (30) and the argument of the cross-spectrum is given by equation (31). The limits given in equation (66) do not necessarily exist for arbitrary stationary time series and hence, equations (67), (30), and (31) are not valid in general. Nevertheless, for time series $f_{1T}(t)$ and $f_{2T}(t)$ which are of finite duration $2T$, we see that equations (60) through (66) are valid if we do not take the limits as T tends to infinity. Hence equations (67), (30), and (31) are valid for time series of finite duration.

ACKNOWLEDGEMENTS

We should like to express indebtedness to the Magnolia Petroleum Company for supplying us with the seismograms and for the many helpful discussions with members of their staff through the years. Grateful acknowledgement is made to S. M. Simpson, and to our other colleagues H. W. Briscoe, M. K. Smith, and W. P. Walsh, who are associated with the MIT Geophysical Analysis Group. Also we should like to thank Miss Virginia Woodward who did a large part of the computing work presented in this paper and Miss Barbara Halpern for typing the manuscript.

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    - A- 2 Preliminary Report on Prediction of Pacific High.
    - A- 3 Temperature Variations Study.
    - A- 4 Preliminary Study of Predictions of Daily Temperatures.
    - A- 5 Path of Pacific High Study.
    - A- 6 Methods of Combining Auto-Correlation Coefficients.
    - A- 7 Properties of Auto-Correlations.
    - A- 8 Long Range Temperature Auto-Correlation Functions.
    - A- 9 Temperature Correlations.
    - A-11 Prediction by Continuous Revision of Coefficients.
    - C- 3 Prediction of Daily Mean Temperatures for Columbus, Ohio.
    - C- 4 Prediction of Daily Mean Pressures for Columbus, Ohio.
    - C- 5 Preliminary Pressure Map Prediction.
    - C- 6 Linear Predictability of Polar Processes.
    - C- 8 Alaskan Trial Study.
    - C- 9 Dutch Harbor Periodicities.
    - C-11 Considerations of Limitations of Linear Predictions of Pressures.
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Rep. No. 8, 1950: Statistical Prediction of Migratory North American Anticyclones: An Introductory Attack Upon Non-Stationary Time Series in Weather

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SIGNAL-TO-NOISE RATIO IMPROVEMENTS BY FILTERING AND MIXING*

HAROLD R. FRANK† AND WILLIAM E. N. DOTY‡

ABSTRACT

This paper is concerned with the signal-to-noise (interference) amplitude ratio of seismograms. The problem of improving the signal-to-noise ratio by filtering and mixing is approached quantitatively. Records of known signal-to-amplitude ratio and known frequency content were made employing multiple-trace variable area equipment such that identical energy was reproduced and re-recorded through various filtering and mixing schemes and comparisons made. Equipment effects on wavelet character and stepout times are illustrated.

The advent of practical multiple-channel recording and reproducing equipment has made it possible to maintain a record analysis service for the benefit of seismic crews operating in poor record areas. This service involves broad-band recording of the seismic energy in reproducible form such that the energy can be analyzed in greater detail than in the past. Much of the analysis can be conducted in the laboratory, which is more conducive to detailed experimentation than are field conditions. Also, laboratory equipment can be much more elaborate. The purpose of the analysis is to establish the optimum filtering and mixing arrangements for a particular area and shot hole condition. The results obtained from optimum filtering and mixing arrangements are often superior to the results obtained by the conventional field equipment using normal equipment adjustments. The difference in results is so striking, in many cases, that the interpreting personnel are hesitant to accept the improved results as data. This cautious attitude assumed by the interpreters is not completely unjustified, since the equipment characteristics used to obtain the superior results are sometimes extreme compared to characteristics previously employed in the field equipment.

It was decided that a controlled test, showing signal-to-noise improvement effected by frequency and phase discrimination, might serve to justify relatively extreme equipment adjustments in a quantitative way. As a consequence, more confidence would be established in the minds of the too-cautious interpreter. These tests would also serve to illustrate more clearly detrimental effects associated with extreme equipment characteristics.

The test required a reproducible record having known signal and noise amplitude ratios, frequency spectra, and known signal position.

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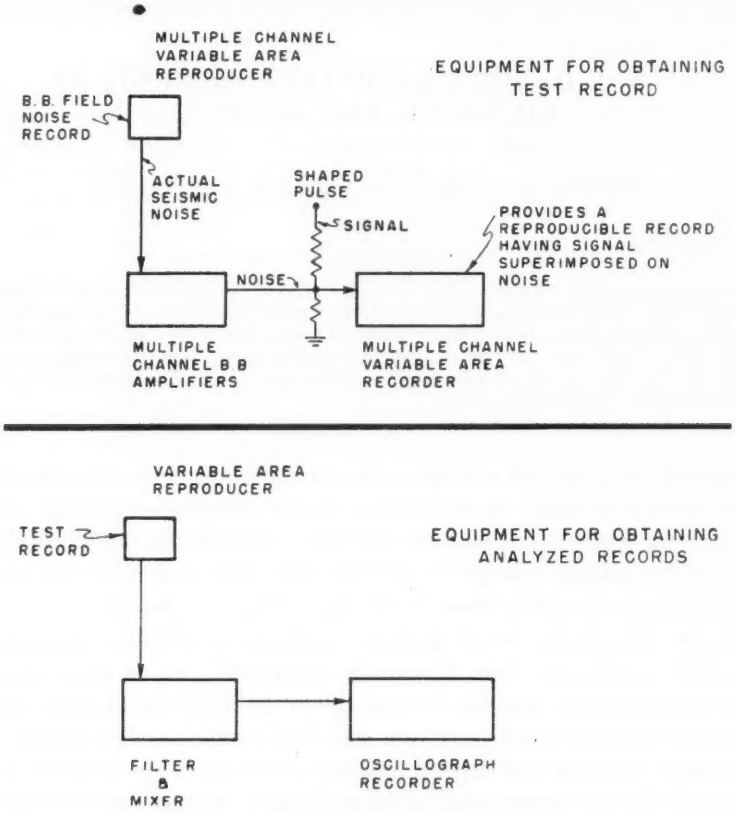

FIG. 1. Preparation of basic test record.

This basic test record was prepared as shown on Figure 1. The block diagram of the equipment setup providing the test record is shown on the top portion of the figure. A particularly poor seismic record from a poor record area was reproduced and re-recorded in reproducible form with controlled amplitude of pulses superimposed at intervals along the record. These pulses were shaped to closely approximate observed seismic reflection pulses and will be called "signal." The reproduced seismic disturbance will be considered "noise." The pulses were recorded on one trace, signal only, so that the signal wave form could be observed and also serve as a key trace. The bottom portion of this figure shows the equipment setup for subjecting the test record to different filtering and mixing arrangements.

Figure 2 shows two segments of the broad band record having signal pulses superimposed on each trace of noise; the amplitude, wave form, and time position of these pulses are indicated by the key trace. Also in this figure are plots of signal frequency spectra and noise frequency spectra. These plots show the relative amplitude of the frequencies present in the particular wave forms. The signal frequency spectrum was obtained from the key trace and the noise fre-

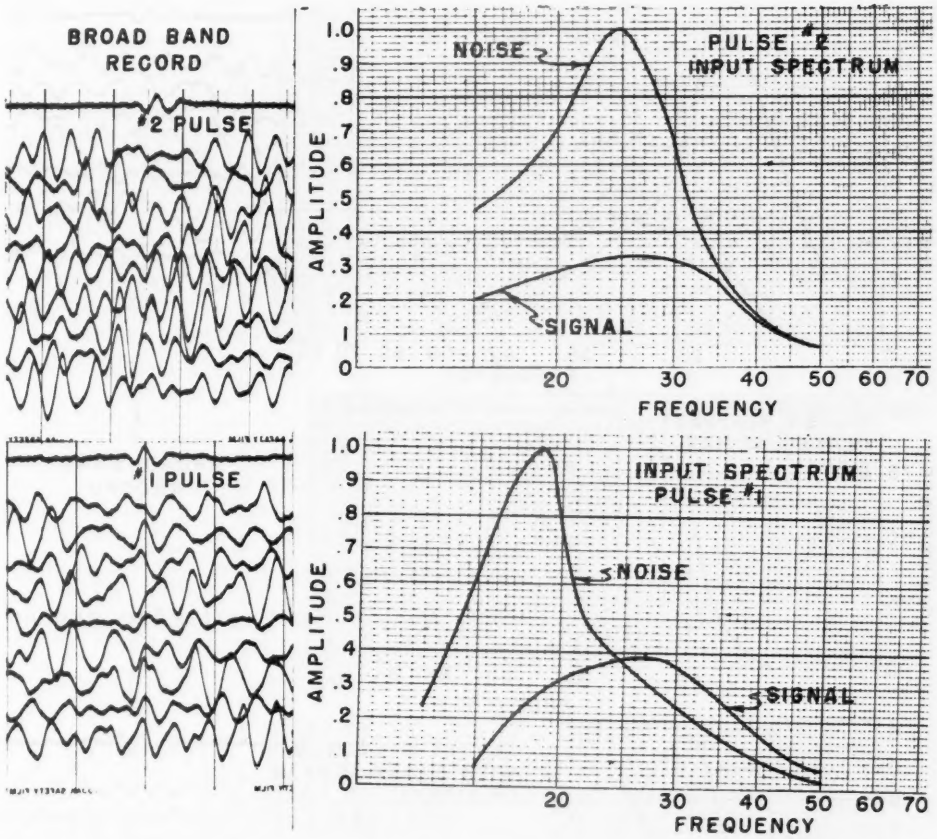

FIG. 2. Records with signal pulses (shown at top of each) superimposed on each trace of "noise." Spectra are shown on plots at right.

quency spectrum was obtained from an average of the spectra of individual traces of noise only, taken in the immediate vicinity of the applied signal. A mechanical Fourier analyzer was used to determine these frequency spectra because of its greater accuracy as compared to electronic filter analyzers. The frequency spectra and phase plots completely describe the traces for the time interval analyzed. The phase plots do not contribute substantially to this discussion, consequently they have not been included.

The noise spectrum for the case designated as No. 2 is peaked very close to the peak of the signal spectrum, making it quite difficult to separate the signal from the noise. This case will be discussed in detail later in the paper.

The case designated as No. 1 has a noise spectrum peaking somewhat lower than the signal. The peak amplitude of the noise is approximately $2\frac{1}{2}$ times the peak amplitude of the signal, giving a signal-to-noise ratio of 0.4 to 1, much less than is required to make a positive pick across the nine traces, as is demonstrated

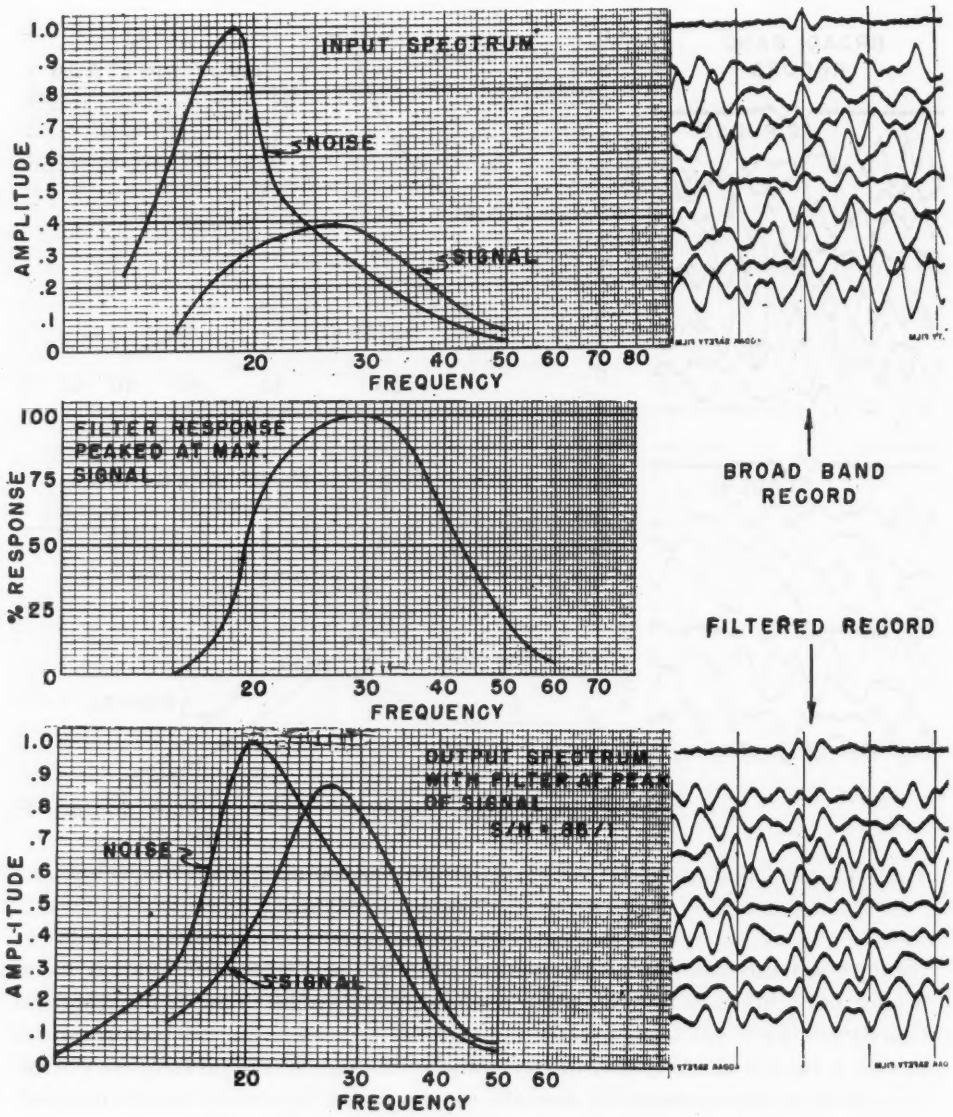

FIG. 3. Effects of a filter peaked at the peak signal content.

by the broad-band record. These conditions of signal and noise were selected as being representative of poor or marginal record areas in which a limited degree of improvement can transform useless records into useful records.

It is easy to prepare test cases in which the noise-to-signal ratio is large, but the frequency spread between signal and noise is also large so that satisfactory signal-to-noise ratios are established with more or less haphazard filtering and little or no mixing. These cases would correspond to good record areas in which critical analysis is not required or justified.

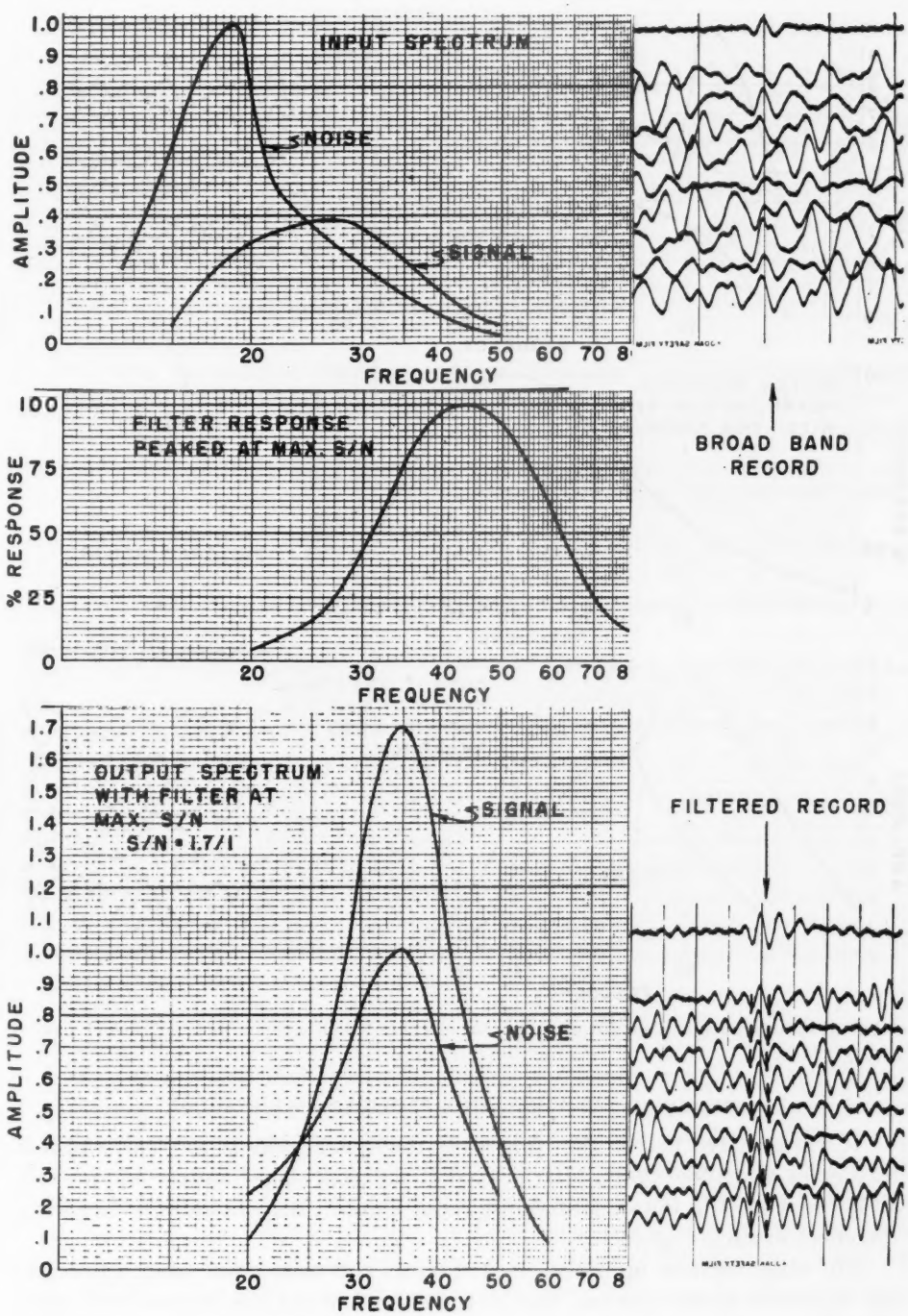

FIG. 4. Effect of optimum "sharp" filter for the same case.

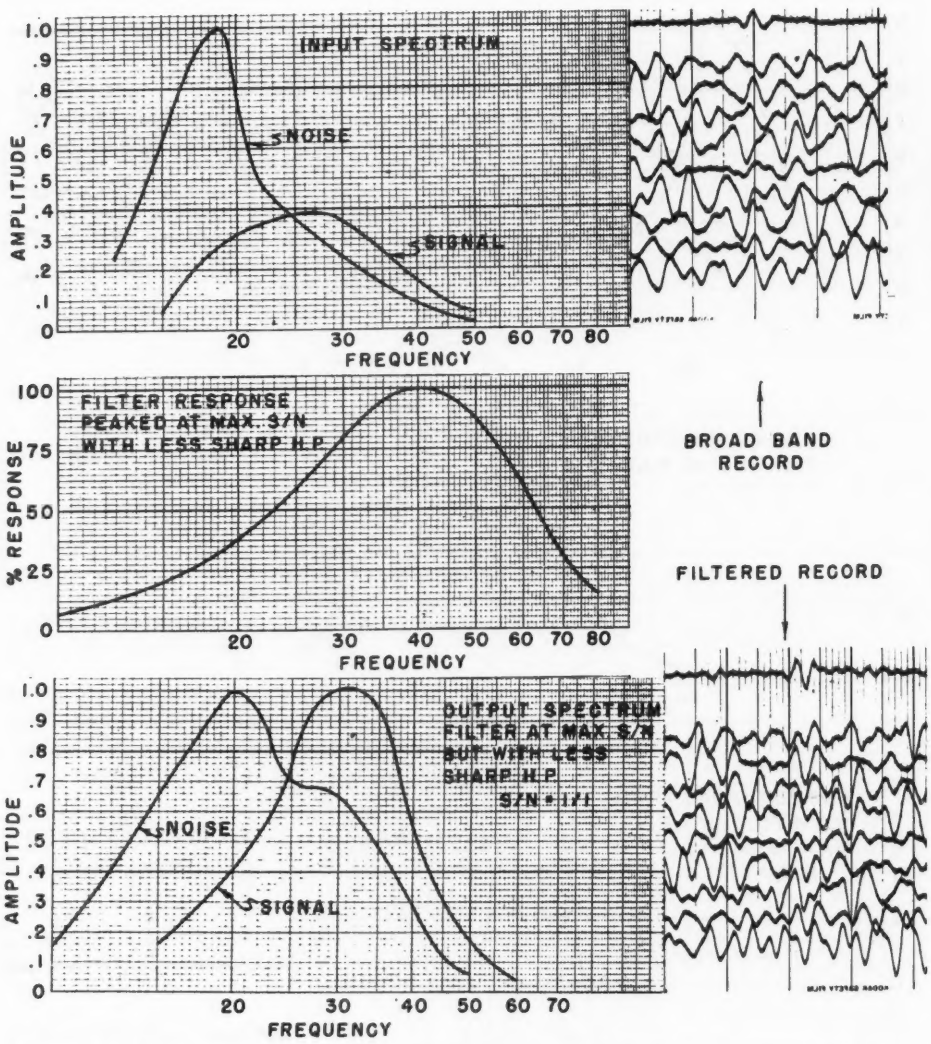

FIG. 5. Filter peaked at same frequency as that of Figure 4 but having a more gentle high pass cutoff rate of 13 db/octave.

FREQUENCY DISCRIMINATION PROVIDED BY FILTERING

It will be noted that in the No. 1 case, the signal peaks at 27.5 cps, and it is reasonable to assume that a filter peaked at the peak signal content will provide an improvement in the signal-to-noise ratio. Figure 3 demonstrates in two ways the effect of such a filter.

The filter response multiplied by the signal and noise input spectra provides the respective output spectra, that is, the filtered record has the modified signal and noise spectra shown. It will be noted that the peak signal-to-peak noise am-

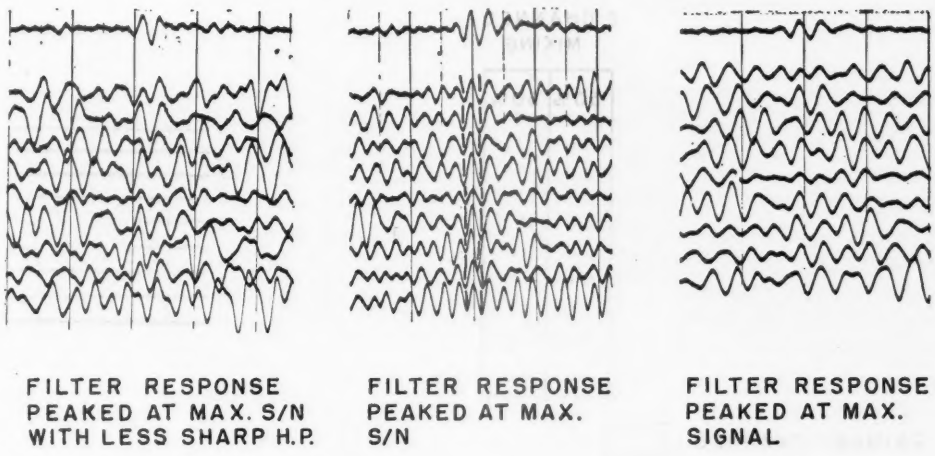

FIG. 6. Comparison of various filter schemes upon the signal-to-noise ratios.

plitude-ratio is improved from 0.4 to 1.0 to 0.86 to 1.0, but as the record demonstrates, this is not sufficient to provide a positive pick.

The next attempt at filtering is based upon a closer inspection of the input spectra. Note that there are frequency components of the signal which are approximately twice the amplitude of the noise components at those same frequencies. This maximum ratio of signal-to-noise occurs above 30 cps. Therefore, a filter which discriminates sharply against frequencies lower than 30 cps should provide output traces having a substantially improved signal-to-noise ratio.

Figure 4 shows the filter response having a high rate of cutoff passing through the vicinity of maximum S-N ratio such that lower frequencies are rapidly attenuated. Again, the input spectra are multiplied by the filter response to obtain the output spectra. Note that the peak signal amplitude to peak noise amplitude is approximately 1.7 to 1.0, and a positive pick is evident on the traces. This filter has provided an increase in signal-to-noise ratio of $1.7/0.4 = 4.2$ times. This filter will be referred to as the optimum filter for this case.

The two filters used for the previous illustrations had a maximum cutoff rate of approximately 40 db/octave on low-pass and high-pass sides. This will be referred to as sharp filtering in this paper. It is realized, of course, that what constitutes sharp filtering is a matter of opinion, but it is believed that 40 db/octave is a sharper cutoff rate than many are using at the present time.

In order to justify sharp cutoff rates, Figure 5 was prepared showing a filter peaked at the same frequency and having a low pass cutoff the same as that of the optimum filter shown in the preceding figure but having a more gentle high pass cutoff rate of approximately 13 db/octave. This filter operates on the input spectra to provide the output spectra shown. The peak amplitude of signal to peak amplitude of noise is 1.0 to 1.0 compared to 1.7 to 1.0 in the case of the

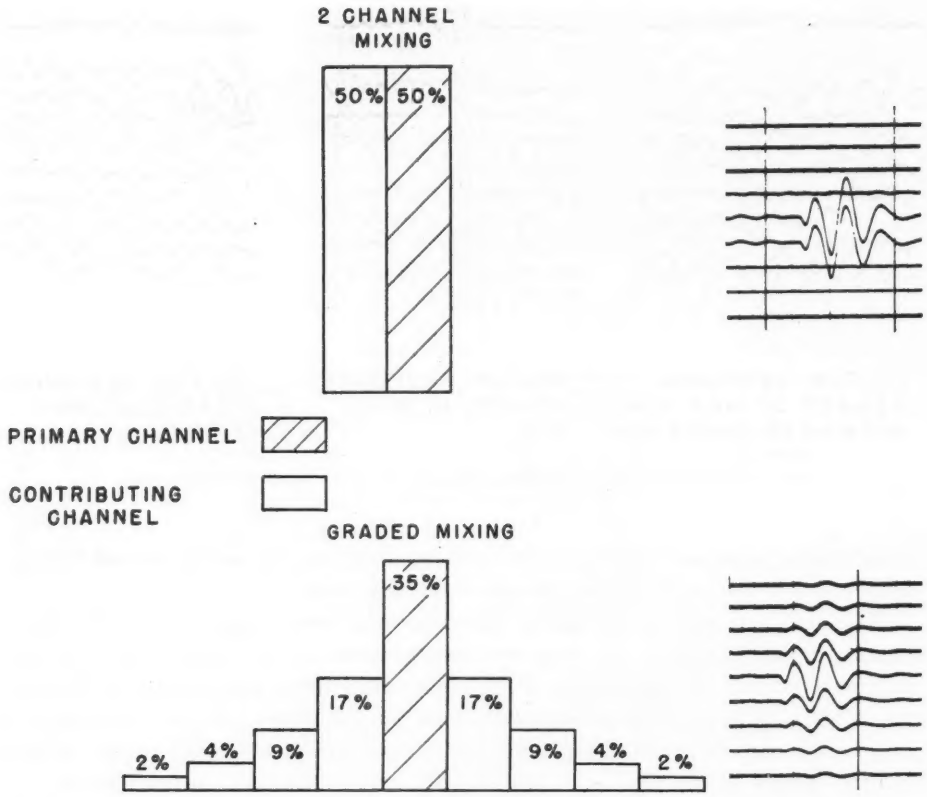

FIG. 7. Comparison of two channel mixing and graded mixing as employed in following illustrations.

sharper filter. The filtered record shows the low frequency disturbance indicated to be present by the spectrum plot. An inspection of the noise spectrum shows that it rises at approximately a 40 db/octave rate between 27 and 18 cps; consequently, if the 18 cps noise is to be rejected to a level below the 27 cps noise, a filter slope of 40 db/octave must be used. That is, in order to maintain the ratio of signal-to-noise amplitude occurring at a particular frequency, the rejection of the filter must at least equal the rise of the noise spectrum. To better compare the effect of the various filtering schemes upon the signal-to-noise ratios, Figure 6 is shown.

PHASE DISCRIMINATION PROVIDED BY MIXING

The improvement of signal-to-noise ratios by frequency discrimination has been discussed; now we consider phase discrimination, effected by mixing, as a means of further improving the signal-to-noise ratio.

A diagram is shown in Figure 7 describing the types of mixing employed in

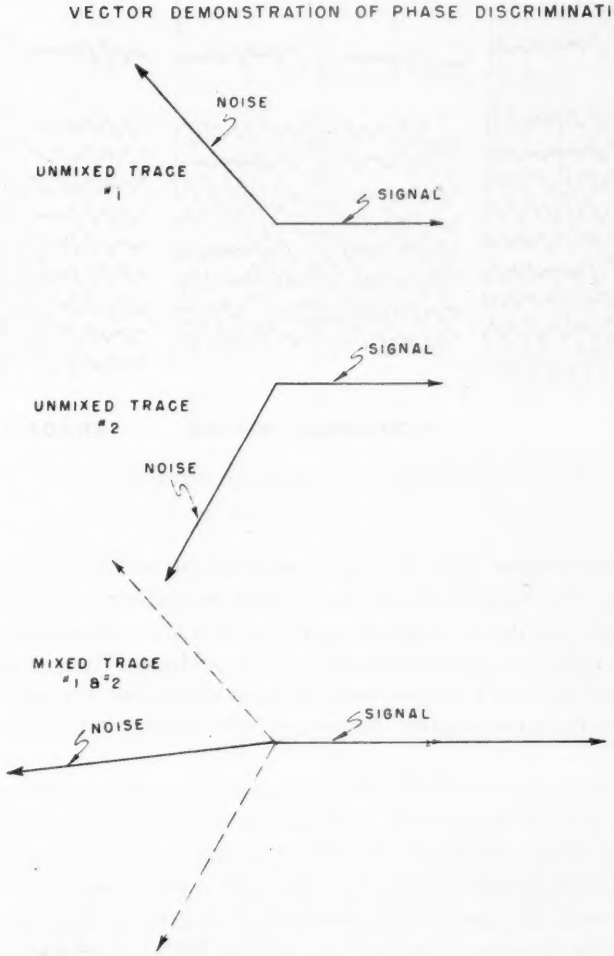

FIG. 8. Simple vector addition of signal and noise for two traces.

the illustrations to follow. The types of mixing to be considered will be referred to as o mixing (no mixing); two channel mixing; and graded mixing, sometimes referred to as progressive or tapered mixing. It is not implied that these mixing schemes are the best, but they do represent different degrees of mixing.

It is the authors' opinion that most interpreters will accept extreme filtering before mixing. It is often the interpreter's opinion that mixing is a procedure that can be carried out mentally without introducing the detrimental effects electrical mixing might introduce. This is true to a limited extent; however, it can be shown that phase discrimination is a more powerful means of improving signal-to-noise ratio than many realize.

Phase discrimination technique is based upon the assumption that the relative

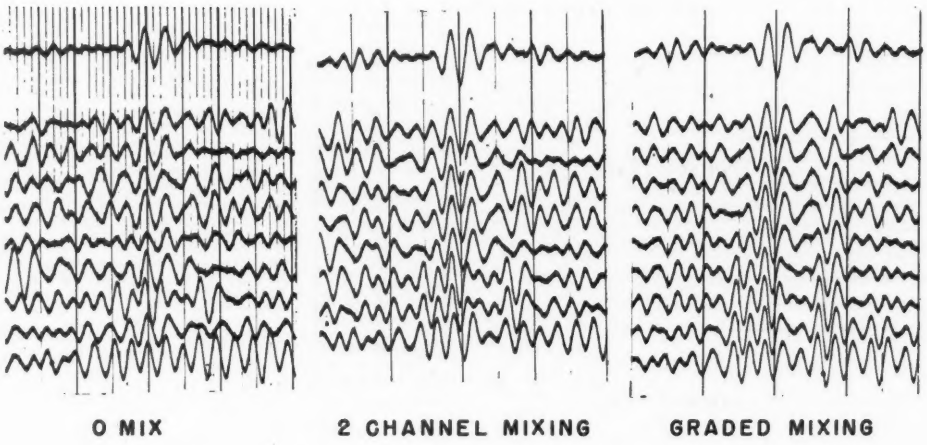

FIG. 9. Effect of mixing on the optimum-filtered No. 1 case.

phase of the signal from trace to trace is reasonably well known. In general, for reflection work, this relative phase from trace to trace is small; consequently, mixing of traces results in a vector addition which is advantageous to signal. Figure 8 demonstrates a case of simple vector addition. Two traces are represented as having noise of a greater amount than signal, but the signal is in phase. Upon addition of the two vectors (or traces), the resultant trace shows more signal than noise.

Figure 9 illustrates the effect of mixing upon the optimum filtered No. 1 case. Note that the pick is much more positive for both two-way and graded mixed traces than for the unmixed traces. There seems to be an upper threshold of signal-to-noise ratio beyond which one does not observe any improvement. The signal-to-noise ratio for the graded mixed traces is greater than that for the two-way mixed traces. However, the two-way mixing did produce a satisfactory pick, so the difference in signal-to-noise ratios is not obvious.

The more difficult No. 2 case will now be considered. Referring to Figure 10, the output spectrum and corresponding record shows that *frequency discrimination alone* does not provide sufficient signal-to-noise ratio to establish a pick; consequently, if mixing provides a positive pick, it can definitely be attributed to improvement effected by phase discrimination.

Figure 11 illustrates the three degrees of mixing for the filtered No. 2 case. It is evident that 0 and two-way mixing do not provide a positive pick, whereas the graded mixing does provide a reasonably good pick.

This illustrates a signal and noise condition in which optimum, perhaps extreme, filtering and a relatively high degree of mixing were necessarily employed in order to extract data. Now the effect of the extreme equipment adjustments upon the reliability of the final data must be considered.

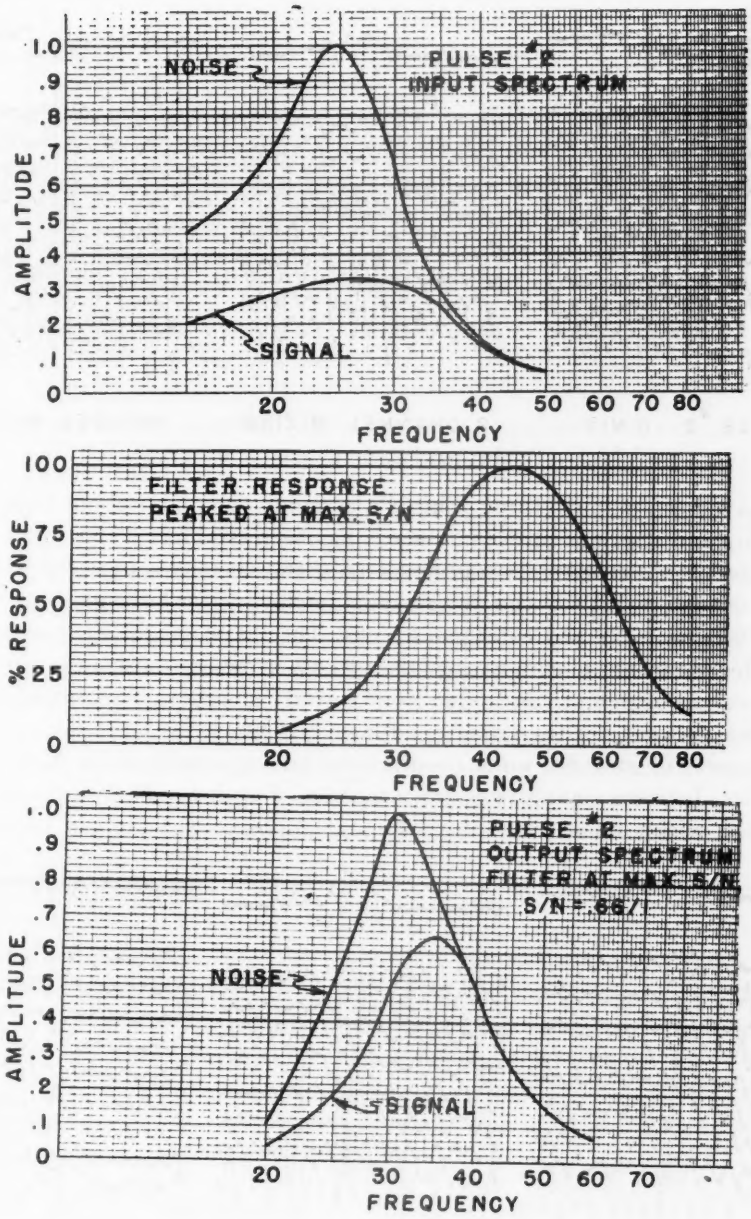

FIG. 10. Spectra for the more difficult No. 2 case.

DETRIMENTAL EFFECTS OF MIXING

One undesirable effect of extreme mixing is evidenced on this same figure. There are picks present which were not introduced as signal pulses. Extraneous

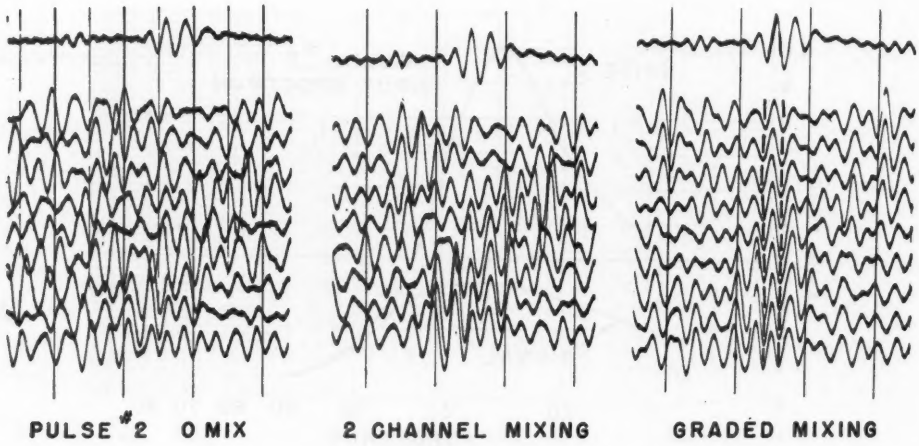

FIG. 11. Effect of mixing on the difficult No. 2 case.

picks have been manufactured. This is a common complaint about high degrees of mixing and a serious problem. Since it has been established that there *were no usable data* without extreme equipment adjustments, the equipment will be accepted in such conditions and criteria must be devised for distinguishing between true reflection picks and extraneous picks. There are several such criteria; one very effective means of eliminating false picks is to ignore those picks not possessing a certain degree of continuity from spread to spread. The probability of a false pick occurring at the same time for several spreads is remote.

Figure 12 illustrates a worse condition for mixing, one in which there is a relative phase between signals from trace to trace. This is the No. 1 case previously discussed, with a linear .026 second stepout imposed. This stepout prevents the

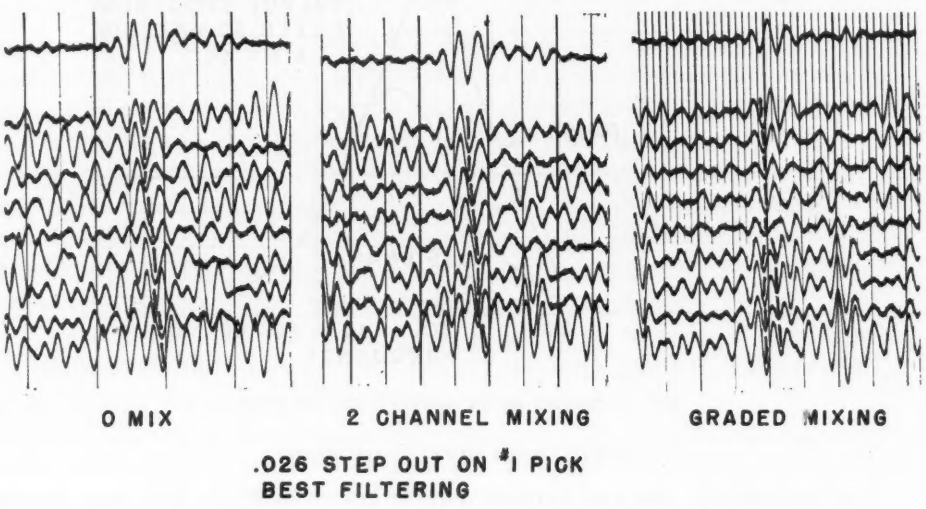

FIG. 12. Difficult condition for mixing occurs when stepout is imposed.

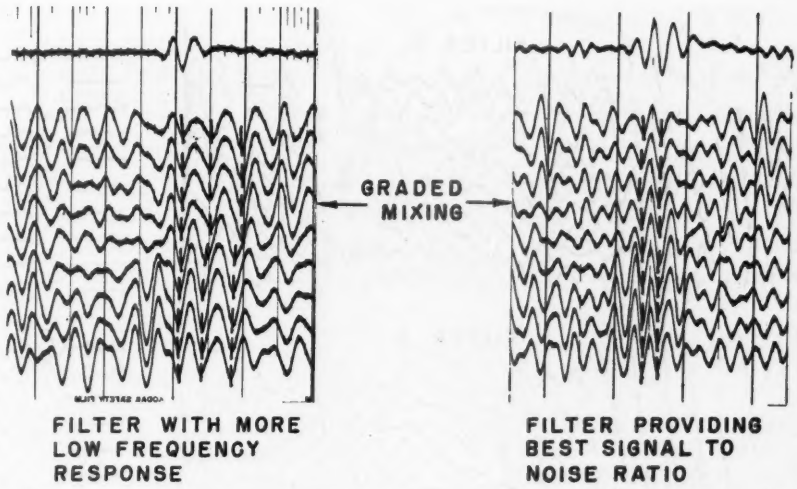

FIG. 13. Comparison of record segments having two types of filtering and identical mixing.

signal from adding to as good an advantage as it did in the o stepout condition. In fact, high degrees of mixing become detrimental to the signal-to-noise ratio at relatively large stepouts. It will be noted that in this case of a fair pick with o mixing, that the two channel mixing provided very little improvement and the graded mixed record is actually inferior. This deterioration of mixed record quality with stepout suggests the desirability of a means for taking out normal stepout, elevation, and weathering effects before mixing, when conditions of low signal-to-noise ratio requiring high degrees of mixing are encountered. This can be done with reproducing equipment, the reverse procedure having been demonstrated on Figure 12.

Figure 13 illustrates what might be a fine point, but one that has been consistently observed in field practice. Record segments having two types filtering, but identical mixing, are shown; the one filter is centered over the signal and the other centered to provide the maximum signal-to-noise ratio. The most outstanding pick on the poorly filtered record has no correlation with the signal pulse and actually has some stepout. The most outstanding pick on the optimum filtered record corresponds to introduced signal. This demonstrates that it is important that the best possible signal-to-noise ratio be established by filtering when a high degree of mixing is to be used.

DETRIMENTAL EFFECTS OF FILTERING

To continue the investigation of equipment effects, it is inevitable that filter ringing be offered as a major objection to sharp filters. The terms "sharp filters" and "ringing" are taken by many as being synonymous.

The following discussion offers two thoughts on this subject. The first thought is that seismic reflection pulses subjected to filters with sharp cutoff rates will not

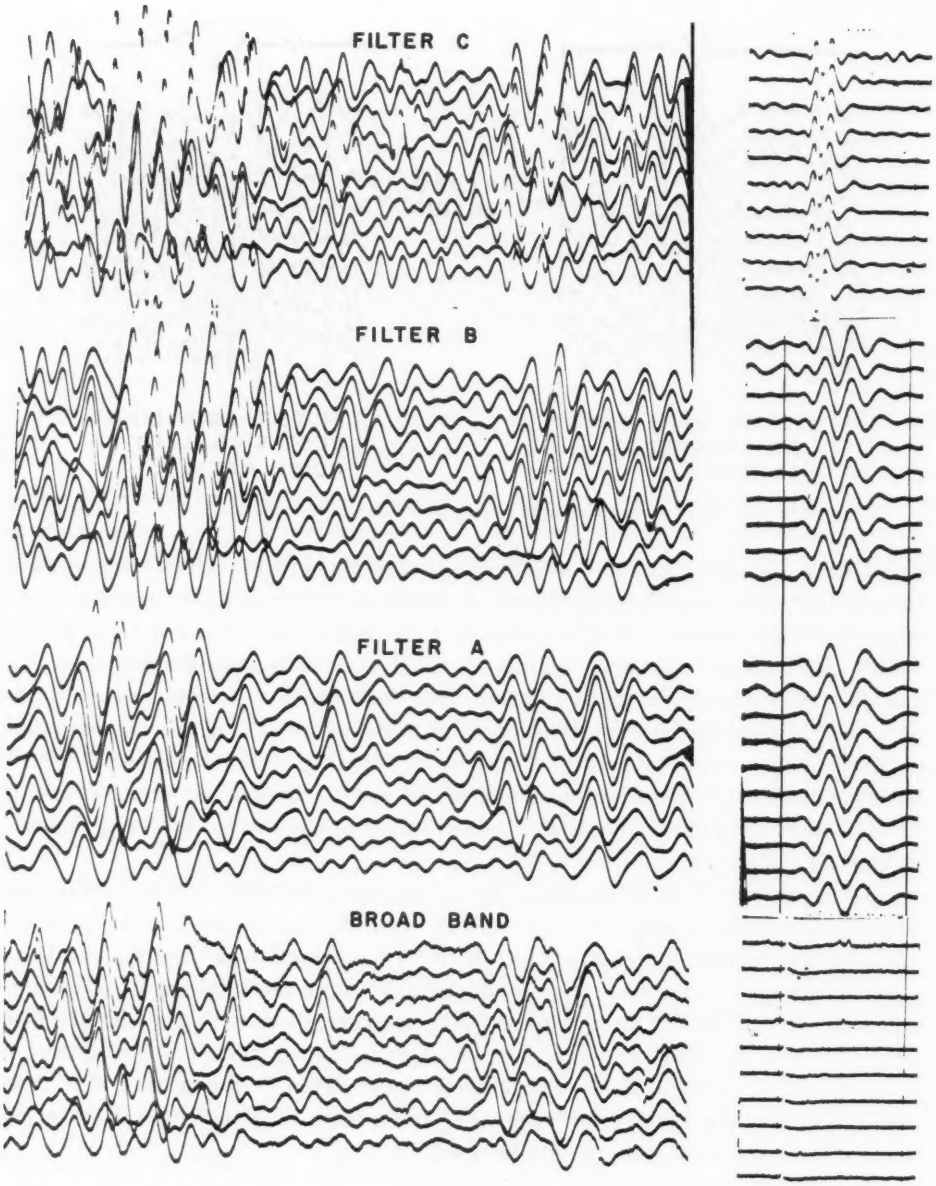

FIG. 14. A record subjected to several filtering schemes for comparison. Filter A has sharp cutoff rates, but record does not have added cycles.

necessarily have added cycles (i.e. "ringing") due to filtering. Figure 14 shows a portion of a broad band recorded field record and this same energy reproduced and subjected to several filtering schemes. This record was selected because of its

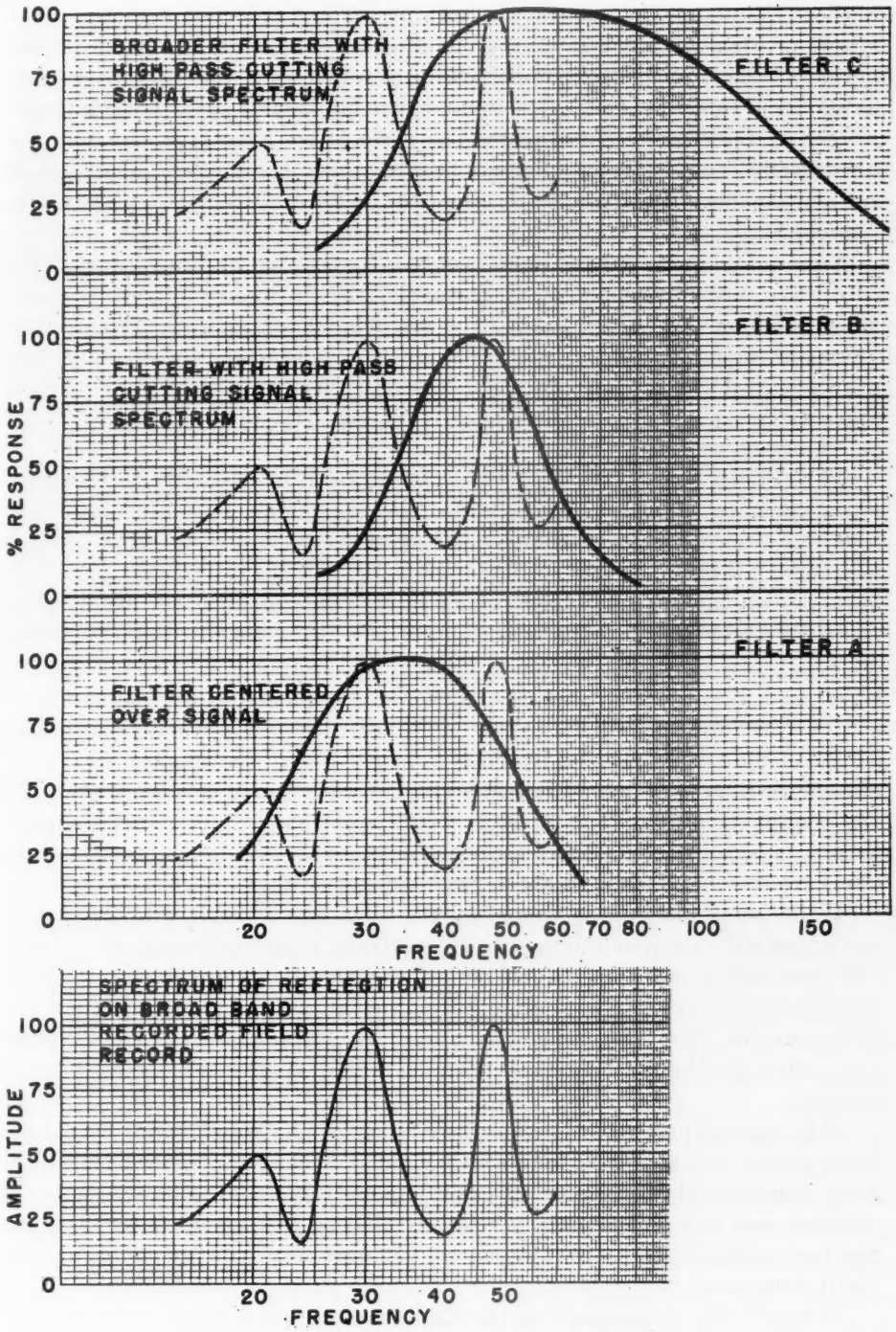

FIG. 15. Filter responses and reflection spectrum for Figure 14.

excellent character. The frequency spectra for the first reflection is shown at the bottom of Figure 15. The rather peculiar frequency spectrum accounts for the unusual character of the reflections. The filter responses of the three filters used are shown in this same figure. The input signal spectrum is shown superimposed on each of the filter response plots. The three filters have approximately the same cutoff slopes, the main difference between them is in the location and band width of the filter. These filters are designated as Filter A, B, and C for purposes of discussion.

Note in Figure 14 that the input energy is transmitted by Filter A with very little wave form distortion; every feature of the broad band traces is easily recognizable on the filtered traces. The filter did reject some high frequencies present in the input and this effect is evident on close inspection of the output wave forms. There are no additional legs or cycles contributed by this filter which has sharp cutoff rates, but which is centered and adjusted to pass the input energy spectrum.

Filter B has the high-pass slope so moved up in frequency that it severely rejects the lower frequency portion of the input spectrum. The output wave form from this filter no longer possesses the character associated with the input wave form. This Filter B provided ringing whereas Filter A did not, even though both have approximately 40 db/octave cutoff rates. Filter C is included to illustrate that band width has not contributed substantially to the ringing. Filter C has the same high pass slope and position as Filter B, but has the low pass moved much higher such that a broad band pass is afforded. Note that Filter C provides an output wave form very similar to that of Filter B. It is now apparent that the rejection of the low frequencies by Filter B and C caused the ringing. The cutoff rates of the filter alone do not fully describe the wave form distortion that will be observed in the output. The input frequency spectrum and filter response plots must both be considered. (The filter phase is ignored in this discussion since these filters are reasonably close to linear phase shift networks.)

If the input spectrum is altered by the filter, it is obvious that the output wave form will correspond to the altered spectrum. It is important to realize that this same ringing appearance would occur if these lower frequencies were removed in any way. If they could be removed mathematically to the same extent the filter removed them, the output wave form would be identical to the filtered case, although the mathematical rejection would involve no electronic components.

It is common practice to check seismic filters for phase and ringing by pulsing them with a unit step function or unit impulse. A dc pulse applied for a very short interval could be considered a unit impulse. These pulses have very broad spectrum and it is understandable that any filtering will severely alter the input spectrum such that the output wave form will bear very little resemblance to the input wave form.

A test of this type appears on the right hand portion of Figure 14. The input pulse is shown at the lower edge of the figure. It is apparent from these records

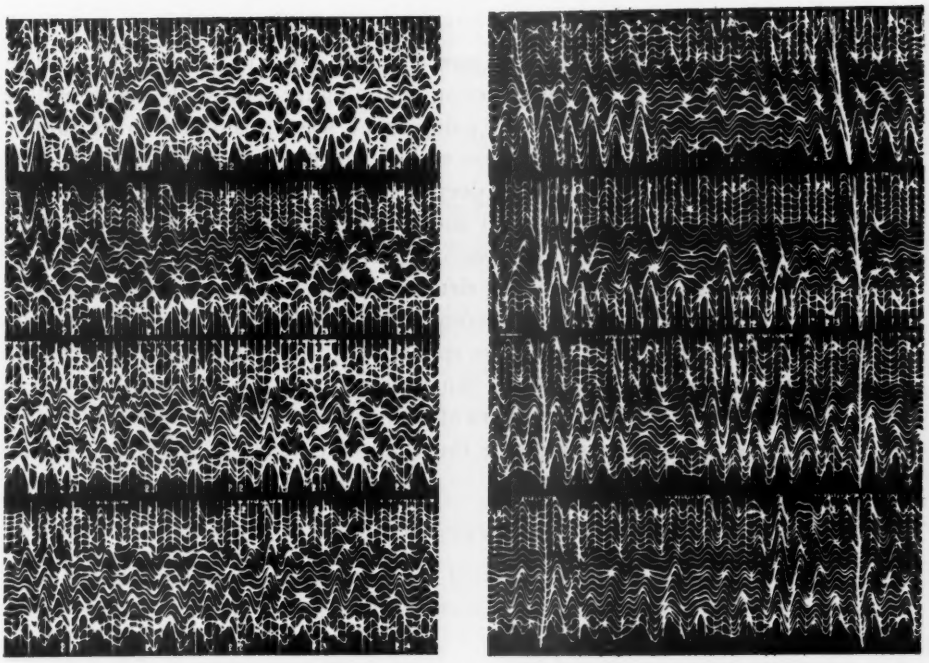

FIG. 16. Signal-to-noise improvement resulting from ground and electronic mixing in conjunction with a filtering scheme which improved the frequency discrimination. Original results on left; improved results from later shooting at right.

that the ringing associated with Filters A, B, and C for the unit impulse type input bears no correlation to the ringing observed from these same filters for the seismic reflection signal input. Therefore, this type of test is not considered an indication of the ringing to expect for a seismic reflection input.

It is true that if a sharp cutoff is employed to reject a portion of the signal spectrum, the output spectrum will be correspondingly sharp and the *time picture* or wave form will ring.

This brings us to the second thought concerning ringing. It is often necessary to accept it in order to obtain time data. The conditions of signal and noise discussed earlier in this paper constitute cases in which a major portion of the signal input spectrum is rejected because it occupies the same spectra as large amplitudes of noise. With so much of the signal spectrum rejected, the remaining components were recorded at a sufficient ratio of signal-to-noise to be apparent; consequently, the real objective, time data, was obtained. The relative time of arrival for the signal at each trace was truly represented by the components of signal passed by the filter. There is, of course, no signal wave form apparent on the broad band record, consequently, it cannot be said that wave form was sacrificed for time data; however, in general, such a trade would probably prove profitable.

A FIELD EXAMPLE OF SIGNAL-TO-NOISE IMPROVEMENT

Figure 16 is shown to demonstrate how signal-to-noise improvement aided in working a particular area. The left portion of the figure represents a segment of a two-spread line recorded last year, using what was considered to be proper filtering and mixing. Although reflection energy can be seen on the records, correlation was difficult, especially in the deeper zones which were of primary interest. The project was abandoned until such time as improved instrumentation could be developed for that area. The second attempt to work the area made use of additional mixing, both ground and electronic, which improved the phase discrimination, in conjunction with a different filtering scheme which improved the frequency discrimination. The same two spreads were shot and the results appear on the right portion of the figure. It can be seen that the record quality was improved sufficiently in the deeper zones of primary interest to allow working this area. There was also improvement in the shallower zones so a better over-all geological picture could be obtained.

CONCLUSION

In conclusion, it is not recommended that extremes of mixing and filtering be used for routine operations unless close control can be maintained such as is provided by reproducing equipment.

ACKNOWLEDGEMENTS

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BASIC THEORY OF THE MAGNETO-TELLURIC METHOD OF GEOPHYSICAL PROSPECTING*†‡

LOUIS CAGNIARD§

ABSTRACT

From Ampere's Law (for a homogeneous earth) and from Maxwell's equations using the concept of Hertz vectors (for a multilayered earth), solutions are obtained for the horizontal components of the electric and magnetic fields at the surface due to telluric currents in the earth. The ratio of these horizontal components, together with their relative phases, is diagnostic of the structure and true resistivities of subsurface strata. The ratios of certain other pairs of electromagnetic elements are similarly diagnostic.

Normally, a magneto-telluric sounding is represented by curves of the apparent resistivity and the phase difference at a given station plotted as functions of the period of the various telluric current components. Specific formulae are derived for the resistivities, depths to interfaces, etc. in both the two- and three-layer problems.

For two sections which are geometrically similar and whose corresponding resistivities differ only by a linear factor, the phase relationships are the same and the apparent resistivities differ by the same proportionality constant which relates the corresponding true resistivities. This "principle of similitude" greatly simplifies the representation of a master set of curves, such as is given for use in geologic interpretation.

In addition to the usual advantages offered by the use of telluric currents (no need for current sources or long cables, greater depths of investigation, etc.), the magneto-telluric method of prospecting resolves the effects of individual beds better than do conventional resistivity methods. It seems to be an ideal tool for the initial investigation of large sedimentary basins with potential petroleum reserves.

INTRODUCTION

There is no doubt that the first positive success in geophysical prospecting was obtained by electrical methods. These have always appeared promising both for oil and mineral prospecting because one can usually expect large resistivity contrasts in earth materials. Moreover, in the case of horizontal bedding, electrical prospecting can give information at locations where neither magnetic nor gravity anomalies can exist. The equipotential method, which involves the mapping of the equipotential lines on the earth's surface when current is introduced into the ground through two point electrodes, usually failed because of difficulty in analyzing the diagnostic features. In spite of the simplicity of Ohm's law, the theory of current flow in the earth is very complex. One may resort to experiments on scale models, but these preserve many of the shortcomings of the theoretical approach when applied to a practical situation.

In general, petroleum and mining geologists were not satisfied with the am-

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† Translated from the French by a professional translator for the Magnolia Petroleum Company.

‡ Translation edited by M. B. Dobrin, R. L. Caldwell, and R. Van Nostrand, Field Research Laboratories, Magnolia Petroleum Company.

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biguous interpretations which geophysicists could offer them on the basis of equipotential data. The use of alternating current is even less desirable in this respect because Maxwell's equations are considerably less manageable than is Ohm's law.

The introduction of resistivity methods was a step in the right direction, chiefly because the "apparent resistivity" of a section whose structure is not too complicated can actually be calculated, or at least estimated, without too much risk of error. However, these new methods, especially with respect to depth determination, have not proved to be as spectacular as they first appeared. Even for the two-layer case, a large amount of labor is involved in developing a master set of curves and one is seldom able to match his experimental curve with any of the curves in his catalogue, extensive as it might be. Moreover, the useful depth of investigation is limited to a few hundred meters in the case of direct current and even less in the case of alternating current, especially at the higher frequencies. In order to investigate to a reasonable depth, it is necessary to use direct current with such great electrode separations that the method no longer has the advantage of being inexpensive.

It is thus evident that electrical sounding, at least in petroleum exploration, originally promised much more than it has realized. However, the relatively recent discovery of the telluric method, although little known and little used outside of France, offers more favorable prospects. Although the principles involved were recognized about 30 years ago by Conrad Schlumberger,* no practical application was made until a few years before World War II. The telluric method has several advantages in that it does away with a current source and the associated long leads, combines flexibility, rapidity, and low cost, and reaches much greater depths of penetration than do ordinary resistivity methods. In spite of its fundamental advantages, however, the telluric method seems to represent only a temporary stage in the development of more advanced methods. The magneto-telluric method, which is the subject of this paper, answers the ever-increasing need for quantitative results. Actually, it is not a strictly electrical method, but rather a combination of telluric and magnetic methods, a combination from which the name of the technique has been derived.

Essentially, the magneto-telluric method involves the comparison, preferably at one and the same place, of the horizontal components of the magnetic and electric fields associated with the flow of telluric currents. The new method offers all the advantages of the telluric method and even improves on it with respect to flexibility, speed, and economy. In addition, it offers the inestimable benefit of making possible, in most cases where the bedding is horizontal, a truly quantitative interpretation. Also, the method can be applied without particular difficulty to submarine prospecting.

* E. G. Leonardon, "Some Observations Upon Telluric Currents and Their Applications to Electrical Prospecting," *Terrestrial Magnetism and Atm. Electr.* 33 (1928), pp. 91–94. A presentation of a report on work dating back to 1921 under the direction of Conrad Schlumberger.

SKIN EFFECT AND ITS CONSEQUENCES. HARMONIC SHEET OF TELLURIC CURRENTS IN AN ELECTRICALLY HOMOGENEOUS EARTH

By way of introduction to the analysis of the magneto-telluric method let us consider a schematic and ideal sheet of telluric current which we shall suppose to be uniform, harmonic, of period T, flowing in a soil electrically homogeneous, of conductivity σ.

During this study, we shall only use electro-magnetic units, both for electric dimensions and magnetic dimensions. Let us choose a rectangular coordinate system o, x, y, z (Fig. 1) such that the origin is on the surface of the ground and oz is the descending vertical. One will notice that on the ground the angle ox, oy is equal to $-(\pi/2)$ for an observer who normally stands with his feet on the ground and his head straight up. It is also useful to remember that, if a current circulates in the ground along ox, oy is at the left of the Amperian man looking up at the sky.

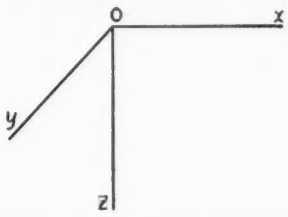

FIG. 1. Coordinate system. xy plane represents earth's surface. z is positive downward.

It is particularly useful when one employs Maxwell's equations and considers a harmonic phenomenon, to bring in the Hertz vector and to make use of imaginary notation. I shall use this approach later, but to handle this first particularly easy case, I prefer to remain as elementary as possible in order to be understood by those who are not familiar with Maxwellian analysis and who are eager to understand the principles of the proposed method.

The term "uniform" when applied to the telluric sheet we want to consider is rather inaccurate. As a matter of fact, there is uniformity only parallel to the surface of the ground, and not along a vertical line. If the density of the current is represented on the surface of the ground, for $z=0$, by

$$I_x = \cos \omega t, \qquad I_y = I_z = 0, \tag{1}$$

the laws of physics show that at depth z one must have

$$I_x = e^{-z\sqrt{2\pi\sigma\omega}} \cos (\omega t - z\sqrt{2\pi\sigma\omega}), \qquad I_y = I_z = 0, \tag{2}$$

e designating the base of natural logarithms. Formula (2) holds for what is called the skin effect. When z increases, one notices an exponential decrease with respect to z at the same time that the phase retardation progressively increases.

Under the conventional name of "depth of penetration" (understood as relating to a layer of conductivity σ and to a telluric sheet of period T) we shall define a term which we are going to use constantly. It designates the depth p when the amplitude is reduced to the fraction $1/e$ of what it is on the surface.

$$p = \frac{1}{\sqrt{2\pi\sigma\omega}} = \frac{1}{2\pi}\sqrt{\frac{T}{\sigma}}. \tag{3}$$

As for the phase, it is retarded one additional radian each time that z is increased by p.

It is obvious that for z infinite, the amplitude of the magnetic field is annulled; otherwise the density of the current could not be zero. At the same time, sym-

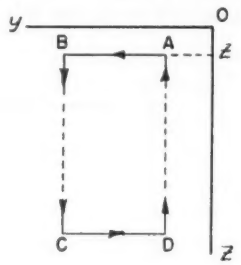

FIG. 2. Path of integration to apply Faraday's Law.

metry requires that the magnetic field be horizontal everywhere, parallel to oy. Let us now apply the theorem of Ampere to a rectangle $ABCD$ with sides AB CD parallel to oy and of unit length, with side AB situated at depth z and with side CD put at infinite depth. It reads

$$H_x = 0,$$

$$H_y(z) = 4\pi\int_z^{+\infty} I_x dz = 2\sqrt{\frac{\pi}{\sigma\omega}}\, e^{-z\sqrt{2\pi\sigma\omega}} \cos\left(\omega t - z\sqrt{2\pi\sigma\omega} - \frac{\pi}{4}\right). \tag{4}$$

In particular, on the surface of the earth, where $z=0$,

$$H_x = 0,$$

$$H_y = 4\pi\int_0^{+\infty} I_x dz = 2\sqrt{\frac{\pi}{\sigma\omega}} \cos\left(\omega t - \frac{\pi}{4}\right). \tag{5}$$

We shall stress this first result, because it is the key to the proposed method: On the surface of the ground, the magnetic field $\mathfrak{H}$ and electric field $\mathcal{E}(E_x = I_x/\sigma)$ are orthogonal. The quotient of the amplitude of the electric field by that of the magnetic field has the value $1/\sqrt{2\sigma T}$. The phase of the magnetic field is retarded by an angle of $\pi/4$ with respect to that of the electric field.

It is well understood that the above result is valid for a telluric sheet flowing

in any direction, provided one always chooses the left hand side as positive in measuring the magnetic field. If, for instance, the component of the electric field along oy is of the form

$$E_y = \frac{I}{\sigma} \cos \omega t, \tag{6}$$

it will be necessary to write

$$H_x = -2\sqrt{\frac{\pi}{\sigma\omega}} \cos\left(\omega t - \frac{\pi}{4}\right), \tag{7}$$

with a change of sign relative to the similar formula (5), since the x axis indicates the right hand side when the current flows along the y axis.

The integral in the second member of relation (5) represents the total intensity of the telluric current through a rectangle, vertical and unlimited, going

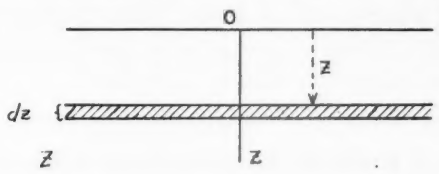

FIG. 3. Section showing horizontal uniform sheet of current.

from the surface, perpendicular to ox, and of unit width. The magnetic field H measures this total intensity within a factor of 4π.

This observation is of great practical importance. *It remains strictly valid for any layered earth, and maintains approximate validity in many cases interesting in exploration.*

Remarks

Assume a horizontal, uniform, extremely thin sheet of direct current of density I, flowing at the depth z between two horizontal planes with sides z and $z+dz$ (Fig. 3). It is well known and easy to show that the magnetic field produced by this horizontal sheet on the surface of the ground is horizontal, that it is directed to the left hand side and that its value is $2\pi I dz$.

For a sheet of direct current, flowing parallel to ox, from the surface of the ground down to depth z, and whose density I_x would be any function of z, one would have

$$H_y = 2\pi \int_0^z I_x(z)dz. \tag{8}$$

Because telluric currents have an extraordinary low frequency, since the length of the wave is enormous relative to p, one might be tempted to apply to them relation (8), assuming their behavior to be that of a direct current, which would lead one to write

$$H_y = 2\pi \int_0^{+\infty} I_x(z)dz, \tag{9}$$

whereas the accurate formula (5) includes the factor 4π, and not the factor 2π.

Units and magnitudes

We measure the magnetic field in γ, the electric field in millivolts/km and the period in seconds. On the other hand, prospectors usually consider the resistivity ρ rather than conductivity σ. They measure resistivities in ohm-meters.

$$\begin{aligned} 1\ \gamma &= 10^{-5} \text{ em cgs} \\ 1 \text{ mv/km} &= 1 \text{ em cgs} \\ 1 \text{ km} &= 10^{5} \text{ em cgs} \\ 1\ \Omega\text{m} &= 10^{11} \text{ em cgs} \end{aligned} \qquad (10)$$

With the new system of units, one obtains:

$$p = \frac{1}{2\pi}\sqrt{10\rho T}, \qquad \rho = 0.2T\left(\frac{E}{H}\right)^2. \qquad (11)$$

In order to become familiar with the order of dimensions, it is useful to consult the two tables of numbers which follow. Table 1 gives the values of p for different values of ρ and T. Table 2 gives, also as function of ρ and of T, the values of H corresponding to an electric field of 1 mv/km.

TABLE 1

DEPTHS OF PENETRATION GIVEN IN KM

$\rho \downarrow \backslash T \rightarrow$	1 sec	3 sec	10 sec	30 sec	1 min	2 min	5 min	10 min	30 min
0.2	0.225	0.390	0.712	1.23	1.74	2.47	3.90	5.51	9.54
1	0.503	0.872	1.59	2.76	3.90	5.51	8.72	12.3	21.4
5	1.13	1.95	3.56	6.16	8.72	12.3	19.5	27.6	47.7
10	1.59	2.76	5.03	8.72	12.3	17.4	27.6	39.0	67.5
50	3.56	6.16	11.3	19.5	27.6	39.0	61.6	87.2	151
250	7.95	13.8	25.2	43.6	61.6	87.2	138	195	338
1,000	15.9	27.6	50.3	87.2	123	174	276	390	675
5,000	35.6	61.6	113	195	276	390	616	872	1510

TABLE 2

AMPLITUDES OF THE MAGNETIC FIELD GIVEN IN γ WHEN E IS 1 MV/KM

$\rho \downarrow \backslash T \rightarrow$	1 sec	3 sec	10 sec	30 sec	1 min	2 min	5 min	10 min	30 min
0.2	1	1.73	3.16	5.48	7.75	11.0	17.3	24.5	42.4
1	0.447	0.775	1.41	2.45	3.46	4.90	7.75	11.0	19.0
5	0.2	0.346	0.632	1.10	1.55	2.19	3.46	4.90	8.49
10	0.141	0.245	0.447	0.775	1.10	1.55	2.45	3.46	6
50	0.0632	0.110	0.2	0.346	0.490	0.693	1.10	1.55	2.68
250	0.0283	0.049	0.0894	0.155	0.219	0.310	0.490	0.693	1.2
1,000	0.0141	0.0245	0.0447	0.0775	0.110	0.155	0.245	0.346	0.6
5,000	0.00632	0.0110	0.0200	0.0346	0.0490	0.0693	0.110	0.155	0.268

From now on, one will notice the extent to which the depths of penetration are exactly adapted to the needs of petroleum prospecting. One will also notice

very large limits between which the ratio of the amplitudes of the electric and magnetic fields may vary, which is, of course, essential when one wants to establish a "precise" method of prospecting in which this ratio is to be measured.

RELATION BETWEEN THE ELECTRIC AND THE MAGNETIC FIELD FOR A NON-HARMONIC TELLURIC SHEET

If the components of the telluric current no longer vary with time according to a sinusoidal law but instead vary in an absolutely arbitrary way, as in natural telluric sheets, the relations obtained above are easily generalized by means of operational calculus. I shall limit myself to give the result, which does not seem to have any great practical interest in connection with prospecting.

$$\begin{aligned} E_y(t) &= -\frac{1}{2\pi\sqrt{\sigma}}\int_{-\infty}^{t} H_x'(u)\,\frac{du}{\sqrt{t-u}} \\ &= -\frac{1}{2\pi\sqrt{\sigma}}\int_{0}^{+\infty} H_x'(t-u)\,\frac{du}{\sqrt{u}}\cdot \end{aligned} \tag{12}$$

In this expression, $H_x'(t)$ designates the derivative of $H_x(t)$ with respect to t.

GENERALIZATION FOR ANY HORIZONTALLY STRATIFIED SECTION

If the earth is formed by a number of horizontal strata of arbitrary thicknesses and resistivities, we shall start from the equations of Maxwell and we shall preferably use imaginary notation, stipulating that all the alternating quantities depend on time through a factor $e^{-i\omega t}$. From now on, this factor will be understood rather than expressed explicitly.

If the harmonic sheet, assumed uniform, flows along ox, the components of the Hertz vector Π along oy and oz are null. Furthermore, Π_z depends only on z (and on t).

The equations of Maxwell are satisfied if

$$\nabla^2\Pi_x + 4\pi\sigma\omega i\Pi_x = 0. \tag{13}$$

The electric field $\mathcal{E}$ and magnetic field $\mathcal{H}$ are expressed in a general way by

$$\begin{aligned} \mathcal{H} &= 4\pi\sigma \operatorname{curl}\Pi, \\ \mathcal{E} &= \operatorname{grad}\operatorname{div}\Pi - \nabla^2\Pi, \end{aligned} \tag{14}$$

and, specifically, in the actual problem by

$$\begin{aligned} H_y &= 4\pi\sigma\frac{\partial\Pi_x}{\partial z}, \qquad & H_x = H_z &= 0 \\ E_x &= 4\pi\sigma\omega i\Pi_x, & E_y = E_z &= 0. \end{aligned} \tag{15}$$

Because, in this case, E_x is proportional to Π_x, we can choose E_x as Hertz vector, so that

$$\frac{\partial^2 E_x}{\partial z^2} + 4\pi\sigma\omega i E_x = 0,$$
$$H_y = -\frac{i}{\omega}\frac{\partial E_x}{\partial z}. \tag{16}$$

Furthermore, we must assure the continuity of E_x and H_y when crossing the different surfaces of separation.

In order to meet condition (16), E_x must be in the form of

$$E_x = Ae^{a\sqrt{\sigma}\,z} + Be^{-a\sqrt{\sigma}\,z}, \tag{17}$$

A and B designating two arbitrary constants and a being defined as

$$a = 2\pi\sqrt{\frac{2}{T}}\,e^{-i\pi/4} = \frac{2\pi}{\sqrt{T}}(1 - i). \tag{18}$$

Let us number from 1 to n the successive formations starting at the surface of the ground. The nth and last one is the lowest stratum. It will be necessary in this layer to put down $A = 0$, because the first term becomes infinite at the same time as z. Furthermore, any solution can always be multiplied by a constant complex arbitrary factor. In other words, the problem is only definite as far as the relative amplitudes and the differences of phase are concerned. For this reason, we can assign an arbitrary value to one of the $2n$ constants A and B. We shall assume that it is constant B corresponding to the bottom stratum which is equal to unity.

In all we have $2(n-1)$ arbitrary constants to meet the same number of conditions at the limits. These conditions are the equality of the two fields at each of the $n-1$ surfaces of separation.

The method of calculation being the same no matter what the value of n, we shall only consider the cases of $n=2$ and $n=3$.

It is obvious that these calculations, which do not present any other complications than the resolution of simple algebraic equations of the first degree, are done exclusively by means of addition, multiplication and division and do not necessitate resorting to integrals or series.

SOURCE OF CURRENTS

The above theory does not concern itself with the origin of the currents involved. Whether the source of these currents are internal to the crust of the earth or whether they are ionospheric, whether these sources are natural (actual telluric currents) or whether they are artificial (vagrant currents), the electromagnetic phenomena inside the earth are the same in every case.

In fact, the reasoning depends only on the requirement that the telluric current sheet be sufficiently uniform. But this uniformity is a matter of experi-

ence. Telluric prospecting proves that in large sedimentary basins this uniformity extends, in an approximate way, over a considerable expanse, often some ten km in width. Such uniformity should be expected all the more if one only considers the very restricted field that enters into a magneto-telluric comparison. Vagrant currents, because of the relative proximity of the sources which produce them, and because of the poor degree of uniformity of the sheets associated with such artificial currents, are feared by the telluric prospectors. On the contrary, they are looked on as a blessing by magneto-telluric prospectors, because they offer sufficient uniformity to meet the requirements of the new method, and they usefully enlarge the spectrum of frequencies.

Readers of *Geophysics*, as well as this writer, are mainly concerned with what is underneath their feet and are little interested in what goes on above their

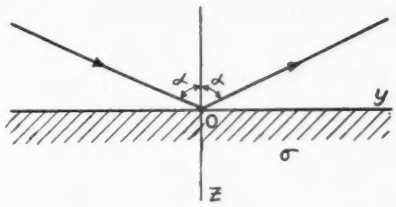

FIG. 4. Plane electromagnetic wave incident upon earth's surface.

heads. However, it may be useful to consider for a few moments longer the nature of the electro-magnetic phenomena as a whole involving the atmosphere.

In the air, where we put down $\sigma = 0$, equation (16) becomes $\partial^2 E_x/\partial z^2 = 0$. E_x appears as a linear function of z, H_y as a constant:

$$\begin{aligned} E_x(z) &= E_x(0) + i\omega z H_y(0); & E_y &= E_z = 0. \\ H_y(z) &= H_y(0); & H_x &= H_z = 0. \end{aligned} \tag{19}$$

A solution of this kind may surprise the reader. One knows, in particular, that the vertical component of the magnetic field of the earth undergoes quick variations whose correlation with those of the horizontal components of the same field or of the telluric field is evident. But the actual solution shows us that H_z is null.

Let us not forget that, in the expression (13) of the equations of Maxwell, we have, from the start, considered as infinite the speed V of electro-magnetic waves in the ground, as well as the speed c of those waves in empty space. For the real phenomenon of propagation we have substituted from the start a fictitious stationary phenomenon. The approximation was quite sufficient for the calculations we had in mind, but it did not permit an accurate picture of the nature of the physical phenomena involved.

Let us suppose that in the atmosphere, a plane wave spreading in the plane oyz hits the surface of the ground at an angle of incidence α (Fig. 4). In order that the conditions at the limits might be met at the surface of the ground,

it is, first of all, necessary that the expressions for the characteristic vectors of the three waves (incident, reflected and refracted) include, respectively, the following factors:

Incident Wave:

$$e^{-i\omega\left(t-\frac{y\sin\alpha+z\cos\alpha}{c}\right)}$$

Reflected Wave:

$$e^{-i\omega\left(t-\frac{y\sin\alpha-z\cos\alpha}{c}\right)}$$

Refracted Wave:

$$e^{-i\omega\left(t-\frac{y\sin\alpha+Kz}{c}\right)}$$

The constant K is chosen to satisfy the equation

$$\nabla^2\Pi + \Pi\left(4\pi\sigma\omega i + \frac{\omega^2}{V^2}\right) = 0. \tag{20}$$

It is thus necessary that

$$K^2 = \frac{c^2}{V^2} - \sin^2\alpha + i\,\frac{4\pi\sigma c^2}{\omega}\cdot \tag{21}$$

But, whereas $(c^2/V^2)-\sin^2\alpha$ is at its maximum equal to unity, it happens that the coefficient of i is enormous. For instance, for $\rho=10\Omega m$ and for $T=30$ sec, it is equal to 5.4×10^{10} so that in practice, and as an excellent approximation, one may write

$$K^2 = 2\sigma c^2 T e^{i\pi/2},$$

$$K = c\sqrt{2\sigma T}\,e^{i\pi/4}, \tag{22}$$

bearing in mind the fact that the coefficient of i in the imaginary part of K must be positive. Accordingly, we justify in the first place the form itself of the expressions (17) which we have adopted initially as a starting point. After that we notice that an infinity of possible waves in the atmosphere can correspond to a given wave in the ground. Not only is α left completely arbitrary since it does not appear in (22), but the state of polarization of the incident wave remains also totally arbitrary. One is entitled to imagine all kinds of miscellaneous phenomena in the atmosphere, and no particular condition is imposed that the vertical component of the magnetic field must be null or negligible.

SPECIFIC STUDY OF THE TWO LAYER PROBLEM

Let us suppose σ_1 to be the conductivity of the upper formation, and σ_2 that of the lower formation, h being the thickness of the upper one (Fig. 5).

Following the general method sketched above, the general expression for

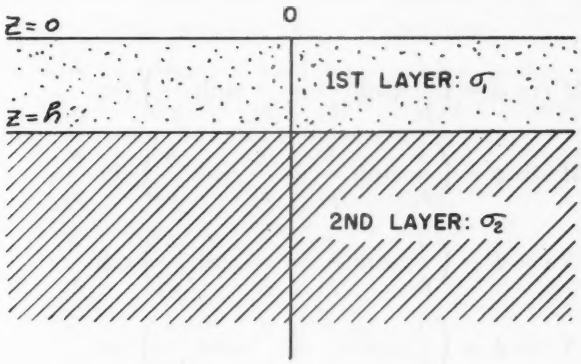

FIG. 5. Two-layer earth section.

the fields will be as follows:

1. In the first formation

$$E_x = Ae^{a\sqrt{\sigma_1}\,z} + Be^{-a\sqrt{\sigma_1}\,z} \tag{23}$$
$$H_y = e^{i\pi/4}\sqrt{2\sigma_1 T}\left[-Ae^{a\sqrt{\sigma_1}\,z} + Be^{-a\sqrt{\sigma_1}\,z}\right].$$

2. In the second formation

$$E_x = e^{-a\sqrt{\sigma_2}\,z} \tag{24}$$
$$H_y = e^{i\pi/4}\sqrt{2\sigma_2 T}\,e^{-a\sqrt{\sigma_2}\,z}.$$

The continuity of E_x and H_y for $z = h$ involves accordingly the two conditions

$$\begin{aligned} Ae^{a\sqrt{\sigma_1}\,h} + Be^{-a\sqrt{\sigma_1}\,h} &= e^{-a\sqrt{\sigma_2}\,h} \\ -A\sqrt{\sigma_1}\,e^{a\sqrt{\sigma_1}\,h} + B\sqrt{\sigma_1}\,e^{-a\sqrt{\sigma_1}\,h} &= \sqrt{\sigma_2}\,e^{-a\sqrt{\sigma_2}\,h} \end{aligned} \tag{25}$$

where

$$\begin{aligned} A &= \frac{\sqrt{\sigma_1} - \sqrt{\sigma_2}}{2\sqrt{\sigma_1}}\,e^{-ah(\sqrt{\sigma_1}+\sqrt{\sigma_2})}, \\ B &= \frac{\sqrt{\sigma_1} + \sqrt{\sigma_2}}{2\sqrt{\sigma_1}}\,e^{ah(\sqrt{\sigma_1}-\sqrt{\sigma_2})}. \end{aligned} \tag{26}$$

The result is an expression for the fields on the surface of the ground. In this expression we shall advantageously introduce the depth of penetration p_1 relative to the first formation and we shall be able to set aside a factor common to E_x and H_y, since we are only interested in the relation between those fields. One has then

$$\begin{aligned} E_x &= Me^{-i\phi} \\ H_y &= \sqrt{2\sigma_1 T}\,Ne^{i(\pi/4-\psi)}, \end{aligned} \tag{27}$$

in which:

$$M\cos\phi = \left(\frac{1}{p_1}\cosh\frac{h}{p_1} + \frac{1}{p_2}\sinh\frac{h}{p_1}\right)\cos\frac{h}{p_1},$$
$$M\sin\phi = \left(\frac{1}{p_1}\sinh\frac{h}{p_1} + \frac{1}{p_2}\cosh\frac{h}{p_1}\right)\sin\frac{h}{p_1}, \tag{28}$$

$$N\cos\psi = \left(\frac{1}{p_1}\sinh\frac{h}{p_1} + \frac{1}{p_2}\cosh\frac{h}{p_1}\right)\cos\frac{h}{p_1},$$
$$N\sin\psi = \left(\frac{1}{p_1}\cosh\frac{h}{p_1} + \frac{1}{p_2}\sinh\frac{h}{p_1}\right)\sin\frac{h}{p_1}. \tag{29}$$

Whereupon:

$$\frac{E_x}{H_y} = \frac{1}{\sqrt{2\sigma_1 T}}\frac{M}{N}e^{-i(\pi/4+\phi-\psi)}. \tag{30}$$

The formulas given above relating to the case of a single formation are at once found again if one starts from those more general expressions and puts down: $\sigma_1=\sigma_2=\sigma$ and $p_1=p_2=p$ whereupon

$$M = N = \frac{1}{p}e^{h/p},$$
$$\phi = \psi = \frac{h}{p}, \tag{31}$$
$$\frac{E_x}{H_y} = \frac{1}{\sqrt{2\sigma T}}e^{-i\pi/4},$$

conforming to the previous result.

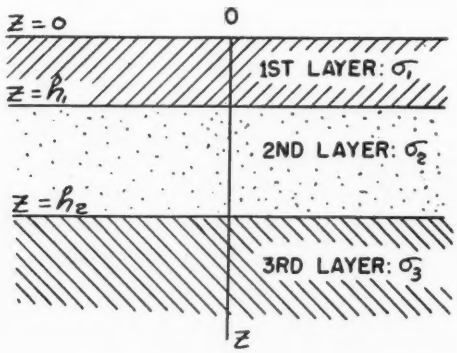

FIG. 6. Three-layer earth section.

FORMULAS FOR THREE FORMATIONS

In the case of three formations of conductivities σ_1, σ_2, and σ_3, when the second one starts at depth h_1 and the third one at depth h_2 (Fig. 6), one uses the following formulas. The ratio between the fields is always in the form

$$\frac{E_x}{H_y} = \frac{1}{\sqrt{2\sigma_1 T}} \frac{M}{N} e^{-i(\pi/4+\phi-\psi)}, \tag{32}$$

by putting down

$$\begin{aligned} h_1\left(\frac{1}{p_1}+\frac{1}{p_2}\right) - \frac{h_2}{p_2} &= u, \\ h_1\left(\frac{1}{p_1}-\frac{1}{p_2}\right) + \frac{h_2}{p_2} &= v, \end{aligned} \tag{33}$$

$$\begin{aligned} M\cos\phi = &\left(\frac{1}{p_1}-\frac{1}{p_2}\right)\left(\frac{1}{p_2}\cosh u - \frac{1}{p_3}\sinh u\right)\cos u \\ &+\left(\frac{1}{p_1}+\frac{1}{p_2}\right)\left(\frac{1}{p_2}\cosh v + \frac{1}{p_3}\sinh v\right)\cos v, \end{aligned} \tag{34}$$

$$\begin{aligned} M\sin\phi = &\left(\frac{1}{p_1}-\frac{1}{p_2}\right)\left(\frac{1}{p_2}\sinh u - \frac{1}{p_3}\cosh u\right)\sin u \\ &+\left(\frac{1}{p_1}+\frac{1}{p_2}\right)\left(\frac{1}{p_2}\sinh v + \frac{1}{p_3}\cosh v\right)\sin v, \end{aligned} \tag{35}$$

$$\begin{aligned} N\cos\psi = &\left(\frac{1}{p_1}-\frac{1}{p_2}\right)\left(\frac{1}{p_2}\sinh u - \frac{1}{p_3}\cosh u\right)\cos u \\ &+\left(\frac{1}{p_1}+\frac{1}{p_2}\right)\left(\frac{1}{p_2}\sinh v + \frac{1}{p_3}\cosh v\right)\cos v, \end{aligned} \tag{36}$$

$$\begin{aligned} N\sin\psi = &\left(\frac{1}{p_1}-\frac{1}{p_2}\right)\left(\frac{1}{p_2}\cosh u - \frac{1}{p_3}\sinh u\right)\sin u \\ &+\left(\frac{1}{p_1}+\frac{1}{p_2}\right)\left(\frac{1}{p_2}\cosh v + \frac{1}{p_3}\sinh v\right)\sin v. \end{aligned} \tag{37}$$

APPARENT RESISTIVITY FOR THE CASE OF TWO FORMATIONS

If the comparison of E_x and H_y is made on a ground which is known to be electrically homogeneous, the relation between those two fields allows one to know the true conductivity (or, if one prefers, its reciprocal, the resistivity), of the formation. If the magneto-telluric comparison takes place on any formation, stratified or not, whose structure is not in general known, it will usually

happen that the phase of H_y with respect to E_x will not be a retardation of $\pi/4$. This will be the first indication that it is heterogeneous. However, no matter what this phase separation might be, we can agree that the modulus of the ratio is equal to $1/\sqrt{2\sigma_a T}$, in which σ_a would be the conductivity of a homogeneous formation which would give the modulus of the ratio between the fields whose value has been experimentally observed. The quantity σ_a is, by definition, the apparent conductivity and its reciprocal ρ_a is the apparent resistivity.

The apparent resistivity is usually a kind of average of the resistivities one meets in a thickness of ground such that density of the current is not to be neglected with respect to its value along the surface. However, it may happen in exceptional cases that the apparent resistivity might be very slightly less than the smallest of the resistivities of the formations, or on the other hand, very slightly greater than the highest of the resistivities. Actually, one knows that a similar phenomenon occurs for the apparent resistivities that are obtained in the prospecting techniques which use a quadripole of measurement supplied by direct current.

In the case of two formations, the apparent resistivity is easily calculated by means of the formulas established above. In accordance with this definition, one has

$$\frac{1}{\sqrt{2\sigma_a T}} = \frac{M}{N}\,\frac{1}{\sqrt{2\sigma_1 T}}, \tag{38}$$

or

$$\rho_a = \rho_1 \left(\frac{M}{N}\right)^2; \tag{39}$$

and

$$\frac{\rho_a}{\rho_1} = 1 + \frac{4\cos\dfrac{2h}{p_1}}{m + \dfrac{1}{m} - 2\cos\dfrac{2h}{p_1}}, \tag{40}$$

if one writes

$$m = \frac{\sqrt{\dfrac{\rho_2}{\rho_1}} + 1}{\sqrt{\dfrac{\rho_2}{\rho_1}} - 1}\, e^{2h/p_1}. \tag{41}$$

The fundamental properties of the apparent resistivity as defined in the technique of electrical sounding, with respect to a certain length of injection line of current, appear again at this point in the apparent resistivity defined now in

regard to a certain period or to a certain penetration depth p. Indeed, one immediately establishes that:

1. if $p_1 = 0$, $\quad \rho_a = \rho_1$,

2. if $p_1 = \infty$, $\quad \rho_a = \rho_2$.

EXPRESSION FOR THE RETARDATION OF PHASE IN THE CASE OF TWO FORMATIONS

The other parameter to consider in order to secure interpretation is the phase retardation of the magnetic field with respect to the electric field. In the case of two formations, it is expressed by

$$\theta = \frac{\pi}{4} + \phi - \psi, \tag{42}$$

with

$$\begin{aligned} \tan \phi &= \frac{m-1}{m+1} \tan \frac{h}{p_1}, \\ \tan \psi &= \frac{m+1}{m-1} \tan \frac{h}{p_1}, \\ \tan (\phi - \psi) &= -\frac{2m}{m^2-1} \sin \frac{2h}{p_1}, \qquad \left(-\frac{\pi}{4} \leqq \phi - \psi \leqq \frac{\pi}{4}\right), \end{aligned} \tag{43}$$

m having the meaning given previously (equation 41).

SPECIFIC CASE OF A SECTION WITH TWO LAYERS, ONE BEING AN EXTREMELY RESISTIVE OR EXTREMELY CONDUCTIVE SUBSTRATUM

In these specific cases, the above formulas become:

1. Extremely resistive substratum:

$$\left.\begin{aligned} \left|\frac{E_x}{H_y}\right| &= \frac{1}{\sqrt{2\sigma_1 T}} \sqrt{1 + \frac{2 \cos 2h/p_1}{\cosh 2h/p_1 - \cos 2h/p_1}} \\ \theta &= \frac{\pi}{4} - \operatorname{arc\,tan}\left(2 \frac{e^{2h/p_1}}{e^{4h/p_1} - 1} \sin 2h/p_1\right) \end{aligned}\right\}, \tag{44}$$

The result becomes particularly simple if h is very much smaller than p:

$$\left|\frac{E_x}{H_y}\right| = \frac{1}{2\sqrt{\sigma_1 T}} \frac{p_1}{h}; \qquad \theta = 0. \tag{45}$$

2. Extremely conducting substratum:

$$\left.\begin{aligned}\left|\frac{E_x}{H_y}\right| &= \frac{1}{\sqrt{2\sigma_1 T}}\sqrt{1-\frac{2\cos 2h/p_1}{\cosh 2h/p_1+\cos 2h/p_1}}\\ \theta &= \frac{\pi}{4}+\arctan\left(2\,\frac{e^{2h/p_1}}{e^{4h/p_1}-1}\sin 2h/p_1\right)\end{aligned}\right\}. \tag{46}$$

The result becomes particularly simple if h is very much smaller than p_1:

$$\left|\frac{E_x}{H_y}\right| = \frac{1}{\sqrt{\sigma_1 T}}\,\frac{h}{p_1}, \qquad \theta = \frac{\pi}{2}. \tag{47}$$

LAW OF SIMILITUDE OF THE MAGNETO-TELLURIC SOUNDINGS

It is known that the interpretation of the ordinary electrical soundings is made much easier by the use of logarithmic scales in the construction of theoretical templates on the one hand, and of experimental diagrams on the other. This use of logarithmic scales is based on the laws of similitude (geometric similitude, electric similitude) which are applicable to electrical soundings.

Laws of similitude of the same kind also govern magneto-telluric soundings and will play an important part in their interpretation. Before we explain how to represent the results we have just obtained in the form of master curves, it is necessary to establish these laws of similitude.

Let us consider two structures, as complex as desired, stratified or not, being geometrically similar, the ratio of similitude being K_L. To make it plainer, let us specify that the corresponding parameters of the two structures will be represented by the same letters, respectively primed and unprimed. In this way, L' and L designating corresponding lengths, we shall put down

$$L' = K_L L. \tag{48}$$

At two similar points of the two structures, the resistivities are ρ' and ρ and we postulate electrical similitude

$$\rho' = K_\rho \rho. \tag{49}$$

Finally, if the periods of the electro-magnetic phenomena are T' and T, we require

$$T' = K_T T. \tag{50}$$

If $\Pi'(x', y', z')$ represents a Hertz vector, which is a solution of Maxwell's equations and of the boundary conditions for the primed structure, let us find out the conditions under which

$$\Pi(x, y, z) = \Pi'(x', y', z') \tag{51}$$

is also a solution for the unprimed structure.

It is necessary to consider equation (51) so that $\Pi(x, y, z)$ designates a function of x, y, z obtained when one respectively replaces in $\Pi'(x', y', z')$ the coordinates x', y', z' by $K_L x, K_L y, K_L z$, which, in other words, makes the same Hertz vector correspond at two similar points of the two structures.

When one has

$$\nabla^2\Pi' = \frac{1}{K_L^2}\nabla^2\Pi; \qquad \sigma' = \frac{\sigma}{K_\rho}; \qquad \omega' = \frac{\omega}{K_T}, \tag{52}$$

the general equation

$$\nabla^2\Pi + 4\pi\sigma\omega i\Pi = 0$$

becomes

$$\nabla^2\Pi' + 4\pi\sigma'\omega' i\Pi' = 0,$$

if

$$K_L^2 = K_\rho K_T. \tag{53}$$

We shall impose this condition.

Besides, one has

$$\mathfrak{H}' = \frac{\mathfrak{H}}{K_\rho K_L}, \qquad \mathcal{E}' = \frac{\mathcal{E}}{K_L^2}; \tag{54}$$

so that the conditions of continuity supposed to be met in one of the structures are also met in the other one.

The ratio E'/H' of an electrical component to a magnetic component is equal to the corresponding ratio with a factor of proportionality, *which is real.* The phase separation between those components is, consequently, the same in both structures.

On the other hand, the ratio ρ_a'/ρ_a of the apparent resistivities has the value

$$\frac{\rho_a'}{\rho_a} = \left(\frac{E'}{E}\right)^2\left(\frac{H}{H'}\right)^2\frac{T'}{T} = \frac{1}{K_L^4}\cdot K_\rho^2\cdot K_L^2\cdot K_T = K_\rho, \tag{55}$$

if we take (53) into consideration. In other words, when one goes from one structure to the other, the apparent resistivities are modified in the same ratio as the real resistivities, which moreover might seem obvious enough on the basis of the principles we have considered.

To sum up the preceding, when one knows the apparent resistivity relative to a certain structure and a certain period T, one deduces at once from this *one* apparent resistivity relative to another structure deduced from the first one by geometrical similitude (ratio K_L) and by electrical similitude (ratio K_ρ). The new apparent resistivity is equal to the former one multiplied by the ratio of electrical similitude and it is relative to a period such that

$$K_T = \frac{K_L^2}{K_\rho} \cdot \tag{56}$$

CONSTRUCTION AND DESCRIPTION OF MASTER CURVES FOR TWO FORMATIONS

A magneto-telluric sounding (in order to abbreviate we shall from now on say MT sounding) will be represented by means of two curves, namely those indicating ρ_a and θ as functions of T. In the preparation of master sets of curves for the case of two formations, it is necessary to consider three arbitrary parameters, namely two resistivities and one thickness, each of which may vary from zero to infinity.

The value of the law of similitude lies in the fact that, in order to represent the whole of the MT-soundings, for two formations, it is sufficient to limit one's self to the specific case of $\rho_1 = 1$ and $h = 1$. In this way there only remains one single arbitrary parameter, namely the resistivity ρ_2 of the substratum, so that the totality of MT-soundings is represented by means of two systems of curves.

Indeed, when, in a more general way, the resistivities of the two present formations will be $\rho_1' \neq 1$ and ρ_2' and when the thickness of the first formation will be $h' \neq 1$, in order to obtain the curve $\rho_a' = \rho_a'(T')$ it will be sufficient to multiply

1. by ρ_1' the ordinates of that one of the curves $\rho_a = \rho_a(T)$ characterized by the ratio ρ_2'/ρ_1' equal in magnitude to the value of the parameter ρ_2.

2. by h'^2/ρ_1' the abscissas of this same curve.

Furthermore, in order to obtain the curve $\theta' = \theta'(T')$, it will be sufficient to multiply by the same factor h'^2/ρ_1' the abscissas of that of the curves $\theta = \theta(T)$ characterized by the value ρ_2'/ρ_1'. There will be no reason to modify the ordinates.

Rather than to carry out these multiplications, it is obviously much easier to choose for each of the systems ρ_a and θ the logarithmic abscissas representing the logarithm of $\sqrt{T}$. Furthermore, for the system ρ_a, the ordinates will represent the logarithm of ρ_a. The two sets of curves reproduced here were constructed in this way, with scales as indicated in Figures 7 and 8.

With the help of these logarithmic master curves, the expansions of the abscissas and of the ordinates described at the beginning of this section will amount from now on to a simple translation. A translation will be carried out parallel to the axis of the abscissas for curve ρ_a, as well as for curve θ, *and this translation will be of the same amplitude in both cases*. Furthermore, in the case of curve ρ_a a second translation will be carried out parallel to the axis of the ordinates.

The whole of the curves of system ρ_a, corresponding to the changing values of ρ_2, have an infinity of points in common, defined by

$$\rho_a = 1, \qquad \cos \frac{2}{p_1} = 0.$$

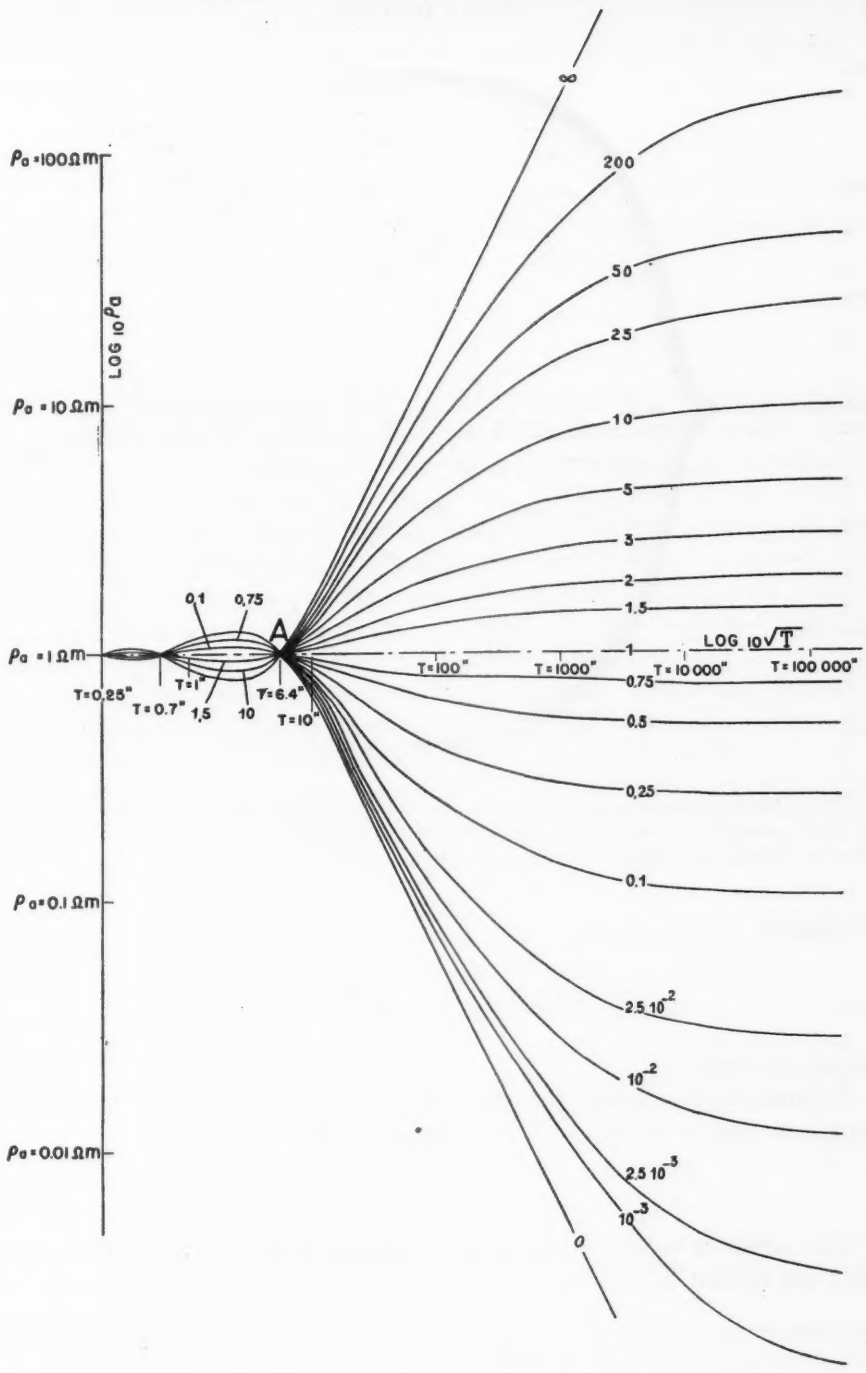

FIG. 7. Master curves of apparent resistivity for magneto-telluric soundings over a two-layer earth. Apparent resistivity plotted as a function of period of the telluric component for various resistivity contrasts. Numbers on the curves show the resistivity of the lower medium in ohm-meters. Resistivity of the upper layer is always 1 ohm-meter.

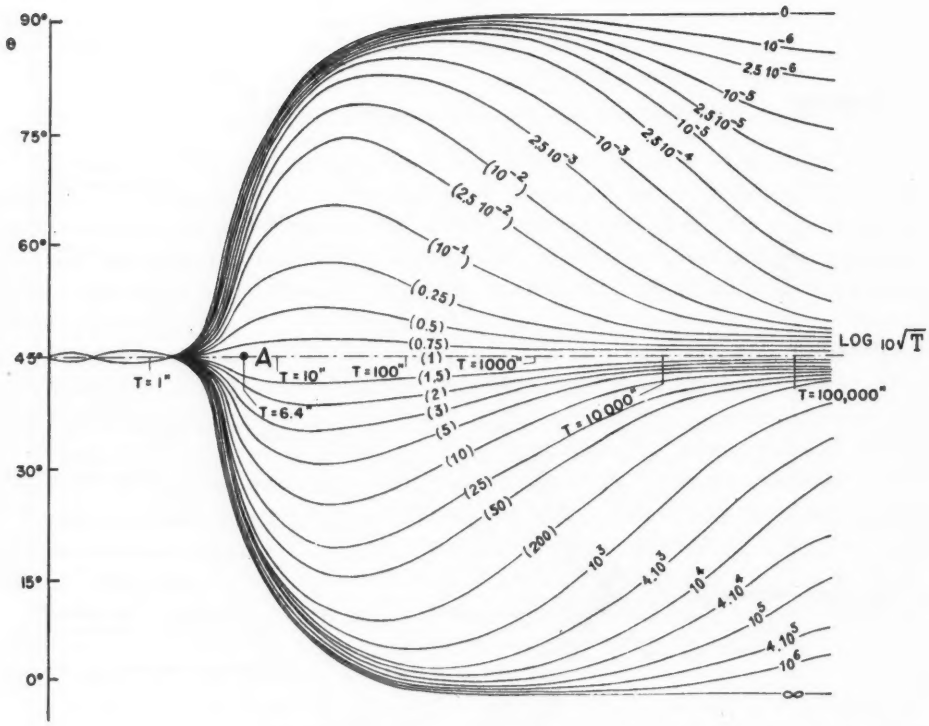

FIG. 8. Master curves of phase differences versus the period of the telluric component for various resistivity contrasts in a two-layer earth. Numbers on the curves show the resistivity of the lower medium in ohm-meters. Resistivity of the upper layer is always 1 ohm-meter.

Whereupon

$$\frac{2}{p_1} = (2n+1)\frac{\pi}{2}; \qquad \sqrt{T} = \frac{8}{2n+1},$$

n being an integer.

Of their common points, the one which is situated the most to the right, and which is marked A on the chart, is consequently defined by

$$\rho_a = 1, \qquad \sqrt{T} = 8.$$

The curves of system θ also have an infinite number of points in common which are defined by:

$$\theta = \frac{\pi}{4}, \qquad \sqrt{T} = \frac{4}{n},$$

n being an integer.

The coordinates of the point which is situated the farthest to the right, are consequently

$$\theta = \frac{\pi}{4}, \qquad \sqrt{T} = 4.$$

In order to make use of the master curves easier, we have marked on the set for θ the point A, having the coordinates

$$\theta = \frac{\pi}{4}, \qquad \sqrt{T} = 8,$$

which means the point having the same abscissa as point A of the curves for ρ_a.

An examination of system ρ_a shows that the apparent resistivity, equal to unity for $T = 0$ approaches ρ_2 when T becomes infinite. The general configuration of system ρ_a is, consequently, the same as that of the abacus for two formations in classical electrical soundings, which we shall designate from now on as E-soundings in order to abbreviate. Let us notice that when T approaches zero, the apparent resistivity only approaches unity by indefinite oscillation on both sides of its limit. In this way, it is sometimes possible to observe apparent resistivities which are *very slightly greater* than the greatest real resistivities of the formations present, or which are, on the other hand, very slightly smaller than the smallest of those resistivities. This phenomenon, a little paradoxical, is also observed, as one knows, in E-soundings, but only starting with three formations.

The examination of system θ shows that θ is equal to $\pi/4$, as well for $T = 0$ as for T infinite. This set of curves, which has no equivalent in E-soundings, is evidently going to provide one of the most useful means of control in MT-soundings.

PRACTICAL USE OF MASTER CURVES FOR TWO FORMATIONS FOR THE INTERPRETATION OF MT-SOUNDINGS

All the calculations and *theoretical* formulas developed in this memorandum imply the use of electro-magnetic units, which may be of any sort providing they are consistent: cgs for instance. We have said previously which electro-magnetic units we should use in the expression of the experimental results (Formula 10). Those units are very practical, but they are neither classical nor self-consistent.

Therefore, it is necessary to specify now that we no longer want to consider our theoretical master curves as relating to the cases of two formations with resistivities 1 and ρ_2. The resistivities in question are $1\Omega m$ and $\rho_2\Omega m$. The depth of the stratum is not 1 but 1 Km. The abscissa of point A is not 8 but $(8/\sqrt{10})$ $(\text{sec})^{1/2}$.

This being established, when we represent graphically the *experimental* results of a real MT-sounding we shall plot as our abscissas the logarithms of the square root of the period expressed in seconds. The ordinates of the curve will be loga-

rithms of the numerical value of the apparent resistivities expressed in Ωm.

In addition to this, we shall adopt the same scales as for the theoretical curves. It is convenient to draw the experimental curves on commercial tracing paper on which cross-section lines are printed. The master curves, on the contrary, are drawn on *plain* Bristol board.

In order to know if the two experimental curves ρ_a and θ are characteristic of a subsurface involving two formations, and in order to know the thickness of the first one, or in other words to carry out an interpretation, one must try, by suitable translations, to bring the two experimental curves into coincidence, on the one hand with curve ρ_a, on the other hand with curve θ, of the theoretical set of curves.

If we are to be entitled to consider the result as satisfactory, it is necessary to insure that the two theoretical curves with which we compare the respective experimental curves correspond to the same value of the parameter ρ_2. Furthermore, the two translations which are to be executed parallel to the axis of the abscissas must be identical. From then on, we shall be able to calculate the resistivities ρ_1' and ρ_2' of the two formations at the same time as the depth h' of the second one.

Point A of family ρ_a, as seen through the transparent tracing paper on which we plot the experimental data, has itself an ordinate whose numerical value is the logarithm of $\rho_1'\Omega m$. Likewise, the asymptote of the theoretical curve ρ_a, considered as sufficient, has *on the tracing paper* an ordinate whose numerical value is the logarithm of $\rho_2'\Omega m$. In other words, the value of ρ_1' and ρ_2' can be read at once on the tracing paper if one does not care for a precision of expression which, in this case, has the inconvenience of making things which are very plain look extremely complicated.

The depth h' remains to be determined. Point A of the one or the other abacus, seen through transparent tracing paper, has an abscissa whose numerical value is $X(\sec)^{1/2}$. Conformably to the laws of similitude, one finds, consequently,

$$K_T = \frac{10}{64} X^2; \qquad K_\rho = \rho_1'.$$

Whereupon

$$K_L^2 = \frac{10}{64} X^2 \rho_1'; \qquad h' = \frac{X}{8} \sqrt{10\rho_1'} \text{ km.}$$

INTERPRETATION IN THE CASE OF ANY STRATIFIED EARTH. RESOLVING POWER OF MT-SOUNDINGS

Let us now supose that one has to deal with three formations, of resistivities ρ_1, ρ_2, and ρ_3. The depth of the second one is h_1 and that of the third formation or substratum is h_2. If the ratio h_2/h_1 is sufficiently great, the influence of the sub-

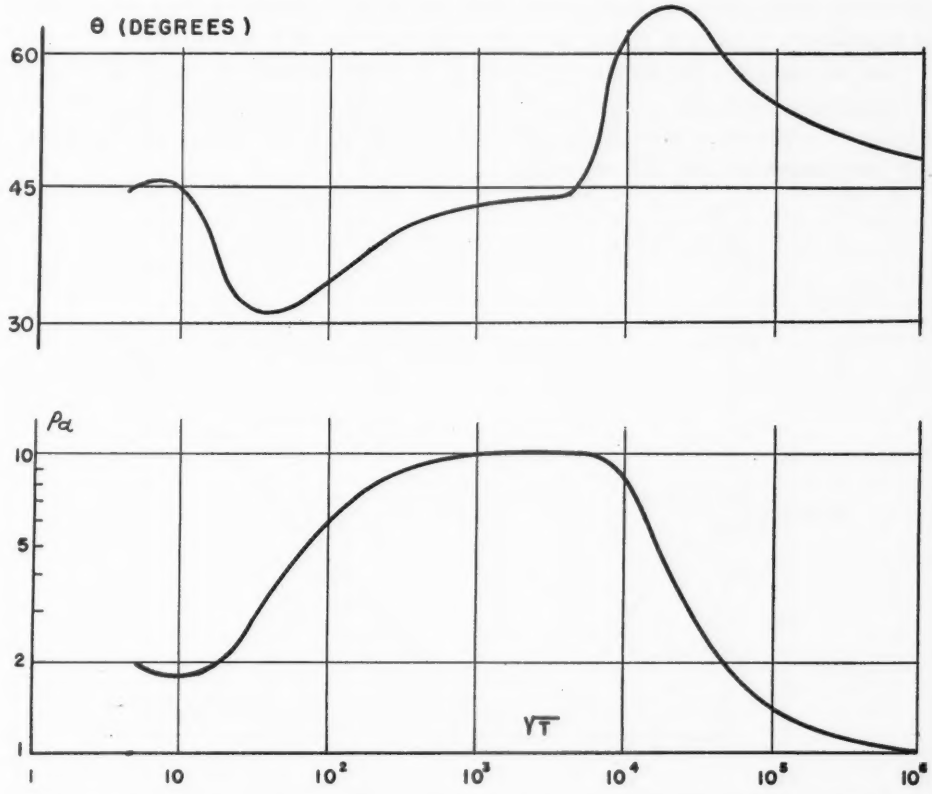

FIG. 9. Computed curves for hypothetical magneto-telluric sounding over three layers in which thickness of second layer is 900 times that of first and in which ρ_1, ρ_2, and ρ_3 are in the ratio of 2:10:1.

stratum starts to be appreciable only for such large periods that the apparent resistivity is already practically equal to ρ_2, while θ has already regained, to a close approximation, its initial value, $\pi/4$. In other words, the influence of the third formation only starts to make itself felt for such periods that the influence of the first formation may be neglected. In order to determine the termination of a graph for three formations of this kind, one is simply led to construct two graphs (ρ_a or θ) for two formations, one after the other. In the second of the graphs for two formations, the formation which is from now on to be known as the first one has the resistivity ρ_2 and the thickness h_2, while the formation from now on to be known as the second one possesses the resistivity ρ_3.

An example of this kind is furnished by Figure 9, in which the ratio h_2/h_1 is supposed to have the value of 900, while the resistivities ρ_1, ρ_2, and ρ_3 are proportional to the numbers 2, 10, and 1.

This highly favorable circumstance in which the master curves for two formations at once allow the interpretation of a sounding carried out over a section

involving more than two formations does not occur if one is dealing with strata of insufficient thickness, either for *E*-soundings or for MT-soundings.

Let us imagine, for instance, a subsoil of three formations, such that h_2/h_1 is equal to 10, while the resistivities ρ_1, ρ_2, and ρ_3 are proportional to 9, 1, and ∞. Figure 10 represents the corresponding *E*-sounding, while Figure 11 represents the two curves for the MT-sounding.

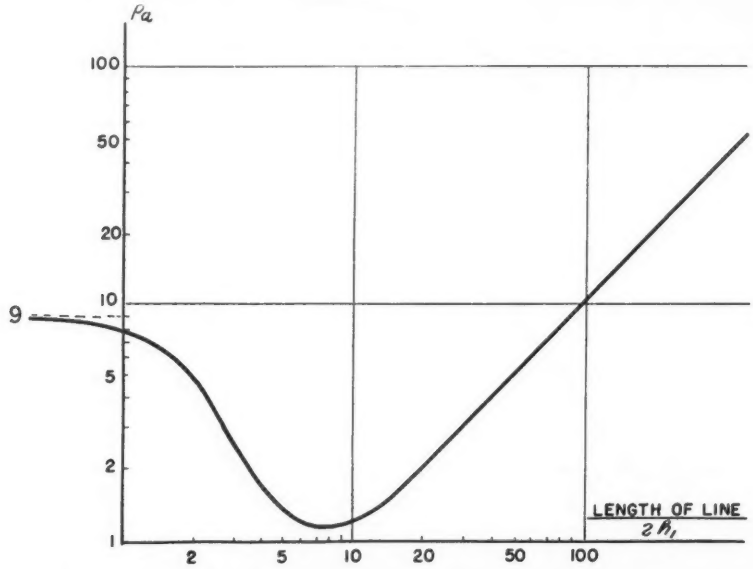

FIG. 10. Computed curve for hypothetical resistivity survey of conventional type over three layers in which thickness of second layer is 10 times that of first and in which ρ_1, ρ_2, and ρ_3 are in the ratio of 9:1: and ∞.

On each of those diagrams, the apparent resistivity, equal to 9 for the short lengths of line (*E*-sounding) or the small periods (MT-soundings), decreases at first when one increases the length of the line or the period, reaches a minimum, and increases indefinitely afterwards. This minimum is not equal to 1, either on the *E*-sounding or on the MT-sounding. One will notice however, that while it is practically equal to 1 in the case of the MT-sounding,* it is only equal to 1.25 in the case of the *E*-sounding. In order to obtain, in the case of the *E*-sounding, with the same resistivities, a minimum practically equal to 1, it would be necessary that the ratio be at least 25.

We shall conclude from this, at first, that the MT-sounding separates the individual effects of the different strata of the subsoil better than the *E*-sounding, and that its resolving power is almost two and a half times higher. Also bearing in mind the additional information furnished by the phase curves, it is consequently

* And even slightly less than unity, because of the somewhat paradoxical phenomenon pointed out when we described the master curve for two formations.

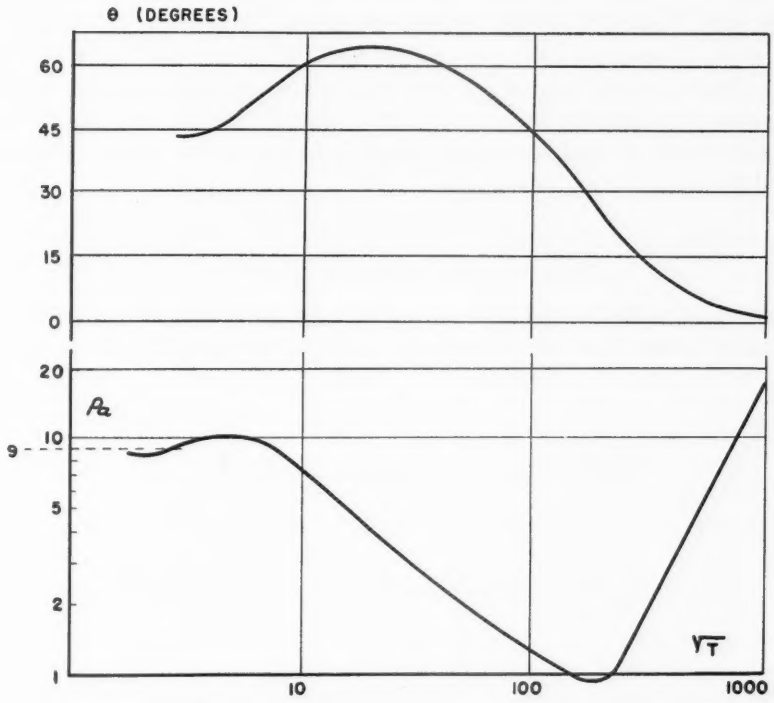

FIG. 11. Computed curves for hypothetical magneto-telluric sounding over three layer configuration of Figure 10.

already very obvious that the MT-sounding allows one to arrive at more precise conclusions than the *E*-sounding, even if one is satisfied with semi-qualitative information.

But still, in the case of MT-soundings, when the problem calls for it, there is nothing to keep us from submitting the semi-qualitative hypothesis we are referring to here to the test of exact calculation. When one has suspected the existence of a certain number of strata, when one has been able to estimate approximately the order of magnitude of their thicknesses and of their resistivities, one can perform the complete calculation of the results that one would obtain if the subsoil presented exactly the supposed structure. If there is disagreement between calculation and experience, one will alter the values formerly assumed for the resistivities and the thicknesses so as to obtain an entirely satisfactory result by a method of successive approximations.

In other words, the MT-sounding can be analyzed by the same method of interpretation one can apply in gravimetry and in magnetism which is so satisfactory for the prospector, but without fear of the disastrous consequences of the fundamental ambiguity which characterizes those last two methods.

Indeed, the calculation in question does not involve integrals nor series, as

we have seen. It can be readily carried out when the general formulas for four, five, or more formations have been established in advance in algebraic form, as we have demonstrated here in the case of two and three formations.

However, it is possible to do much better and to save much time by use of an almost exclusively graphical method which is based on the results which will be obtained in the following paragraph.

APPARENT RESISTIVITIES AND PHASES AT THE DIFFERENT LEVELS INSIDE A HOMOGENEOUS FORMATION

Within a stratified section the complex relation E_x/H_y has a specific value at each level of depth z. We are going to obtain a formula particularly important

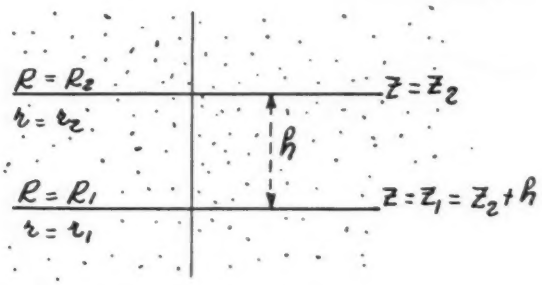

FIG. 12. Geometry for computing relationships between two levels in same medium.

in practice by considering two levels z_1 and z_2 at a distance h, inside the *same* formation of conductivity σ (Figure 12). We shall put down

$$R = -\frac{ia\sqrt{\sigma}}{\omega}\frac{E_x}{H_y} = -i\tan r. \tag{57}$$

The complex numbers R and r are functions of z which represent respectively the values R_1 and r_1 for $z=z_1$ and R_2 and r_2 for $z=z_2$.

A and B designating two constants, we have learned that the expressions for the fields (formulas 17, 18) are of the form

$$\left.\begin{aligned} E_x &= Ae^{a\sqrt{\sigma}z} + Be^{-a\sqrt{\sigma}z}, \\ H_y &= -\frac{i}{\omega}a\sqrt{\sigma}(Ae^{a\sqrt{\sigma}z} - Be^{-a\sqrt{\sigma}z}) \end{aligned}\right\}. \tag{58}$$

One deduces from these that:

$$R = \frac{1+\lambda e^{-2a\sqrt{\sigma}z}}{1-\lambda e^{-2a\sqrt{\sigma}z}}; \qquad \lambda = \frac{B}{A} = Ce^{r}, \tag{59}$$

or in another form

$$\frac{R-1}{R+1}\,e^{2a\sqrt{\sigma}\,z}=\lambda=C^{r}. \tag{60}$$

Consequently, one calculates at once R_2 as a function of R_1:

$$R_2=\frac{R_1(1+e^{2a\sqrt{\sigma}\,h})+(1-e^{2a\sqrt{\sigma}\,h})}{R_1(1-e^{2a\sqrt{\sigma}\,h})+(1+e^{2a\sqrt{\sigma}\,h})}, \tag{61}$$

and, afterwards, r_2 as a function of r_1:

$$\tan r_2=\frac{\tan r_1-\tan(ia\sqrt{\sigma}\,h)}{1+\tan r_1\tan(ia\sqrt{\sigma}\,h)}=\tan(r_1-ia\sqrt{\sigma}\,h), \tag{62}$$

from which finally

$$r_2=r_1-ia\sqrt{\sigma}\,h=r_1+\sqrt{2}\,(h/p)e^{-3i\pi/4}. \tag{63}$$

The indeterminacy of the argument r does not concern us, since we are only interested in the value of R.

It is easy now to go back to the apparent resistivities ρ_a and to the phases θ defined by

$$\frac{E_x}{H_y}=\sqrt{\frac{\rho_a}{2T}}\,e^{-i\theta}. \tag{64}$$

Consequently one has

$$\sqrt{\frac{\rho_a}{\rho}}\,e^{-i(\theta+\pi/4)}=\tan r, \tag{65}$$

and finally

$$\frac{(\rho_a)_2}{(\rho_a)_1}\,e^{-2i(\theta_2-\theta_1)}=\left(\frac{\tan r_2}{\tan r_1}\right)^2. \tag{66}$$

Since the calculations of the prospectors are not usually carried out to 20 decimal places, a simple chart of the complex values of the tangents of a complex argument allows one to calculate an MT-sounding very quickly for $n+1$ formations starting from a sounding for n formations when the $(n+1)$st formation is situated on top of the nth one.

REMARKS

1. In the calculation of a theoretical MT-sounding by an operation of successive approximations, the geophysicist, by constructing his theoretical section through the stacking of strata laid down one on top of the other, proceeds exactly in the same way as nature did when the real strata of the ground were laid down by successive processes of sedimentation.

2. At two stations over a sedimentary basin, the section only differs, in principle and as a first approximation, through the addition—or through the subtraction—of a certain number of superficial

strata. Consequently, it will often be convenient as a first working hypothesis to calculate the complex ratio of the complex quotients E_x/H_y, obtained experimentally at the two stations, a ratio whose interpretation involves only the thickness of the superficial layer, which is different for the two stations.

3. When, for one reason or another, one knows with certainty the resistivities of the ground to a certain depth, it may be easy to omit, through calculation, the influence of this known part of the ground and limit the interpretation only to the unknown subjacent portion.

4. This circumstance occurs in particular when one performs a MT-sounding over a body of water for which the depth and conductivity are known. The former calculation allows one in such a case to correct the MT-sounding for the influence of the sea; in other words, it allows one to obtain, through a very accurate calculation, the diagrams for the MT-sounding that one could have determined experimentally if the water were to have been drained away.

VARIATIONS APPLICABLE TO MT-SOUNDINGS PERFORMED UNDER THE SEA

The measurement of the electrical field at sea does not present any specific technical difficulty. The line of measurement is maintained on the surface of the water through the use of floaters, in the same way as fishermen do with their nets. Moreover, there is no difficulty whatsoever in carrying out a correct galvanometric recording on board of a ship tossed about by the waves. One need only be suspicious if one observes phenomena which have a period the same either as that of the marine currents or as that of the swell, since the electrical currents induced by motion of the conducting water in the magnetic field of the earth do not meet the requirements of the theory we have set forth.

The measurement of the magnetic field offers more serious technical difficulties if one is not willing or able to install a self-recording magnetometer on a series of piles forming a foundation or in an immersed box on the bottom of the sea.

One way of avoiding the difficulty consists in registering the magnetic field *on the ground* and the electric field *in the sea*. The daily experience of prospectors who use the telluric method, has shown, indeed, that in sedimentary beds, the line of the telluric current keeps an almost constant direction over expanses as large as 20–70 km. Besides, this direction would be strictly uniform in a precisely stratified earth.

Now the telluric current, even if it is a variable current, is, approximately conservative because of its very low frequency. As I have already pointed out, the magnetic field is very approximately the same at two stations not too distant from each other on the same straight line ox, since it represents, except for a factor 4π, the total intensity of the telluric current through a stratum of unit width starting from the surface normal to ox.

The argument essentially implies that the two stations are situated on the same straight line ox, perpendicular to the magnetic component one is considering. Consequently, it is very advisable to adhere to this condition if possible. However, experience shows that, in practice, this requirement is not always strictly binding.

These observations will not come as a surprise to observatory geophysicists. Through experience, they are well convinced of the fact that the meaning of their magnetic data does not depend particularly on the electrical resistivity

of the geological strata in the vicinity of their observatory. But, for over a hundred years, since the first observation of telluric current, it has been found that in telluric registrations, on the contrary, one has had to be greatly concerned with the local geologic structure.

Another way to avoid the difficulty consists in observing that in the homogeneous medium formed by the sea water, where a telluric sheet is flowing parallel to ox, the relation between *any* two electro-magnetic dimensions, depending linearly on the Hertz vector, is expressed as a function of parameter λ only (Equation 59). The ratio E_x/H_y is also expressed as a function of λ. In other

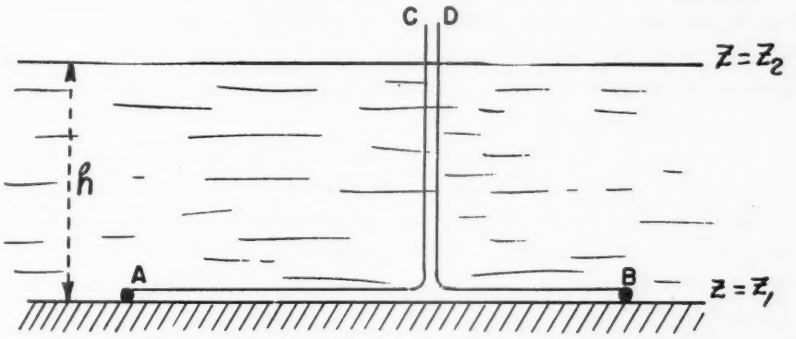

FIG. 13. Configuration of electrodes on water bottom for submarine MT measurements.

words, the study of the relation of any two electro-magnetic quantities is absolutely equivalent to that of the ratio E_x/H_y.

One can, for instance, substitute for the measurement of Hy, the measurement of the electromotive force induced in a large vertical ring parallel to ox, this ring being constructed much more easily on the sea than on the ground. Yet one knows that, if the vertical height of this ring is small so that the magnetic component H_y inside it is almost uniform, the measurement of the induced electromotive force is a classical way of measuring H_y.

It may be easier to substitute for the measurement of the magnetic field H_y that of a second electric field. Let us go back to Figure 11, supposing this time that level z_1 represents the horizontal sea bottom, level z_2 the surface of the water (or, in a more general way, any level between the bottom and the surface of the sea). It is easy to measure the field E_x on the bottom of the sea by means of two immersed electrodes A and B connected with recording equipment on the boat by the two lines AC and BD (Fig. 13).

It can be shown that

$$\sqrt{\rho_a}\, e^{-i\theta} = \frac{2\pi p}{\sqrt{T}}\, e^{-i\pi/4} \frac{\dfrac{(E_x)_1}{(E_x)_2} \sinh\left(\sqrt{2}\, e^{-i\pi/4}\, \dfrac{h}{p}\right)}{1 - \dfrac{(E_x)_1}{(E_x)_2} \cosh\left(\sqrt{2}\, e^{-i\pi/4}\, \dfrac{h}{p}\right)}, \tag{67}$$

in which ρ_a and θ have reference to the apparent resistivity and to the phase relative to level z_1, the level of the bottom of the sea; that is to say, the parameters of an MT-sounding that could be performed on the sea bottom if drained.

CONCLUSION. FIELDS OF PRACTICAL APPLICATION FOR THE MAGNETO-TELLURIC METHOD

It follows from the above that the ideal way to apply the magneto-telluric method consists in performing an MT-sounding as described. When the subsoil is approximatively tabular, the harmonic analysis of the telluric and magnetic diagrams makes it possible to conduct a careful quantitative interpretation which gives us the thickness and the resistivity of the various strata.

The periods higher than one second are exactly adapted to the study of large sedimentary beds and their petroliferous structure. Besides, their recording does not involve serious technical difficulties.

The study of the shortest periods, less than one second, seems technically difficult at the present stage of the art. However, it is less urgent in the light of present needs in geophysical prospecting. It should eventually allow us to adapt the magneto-telluric method to various applications requiring detail of the kind involved in civil engineering studies, in mineral prospecting, and in the search for underground water.

We want to draw attention to the fact that an isolated MT-sounding carried on in the center of a large unknown area can present information similar to that given by a wildcat well in a large scale reconnaissance. For instance, the measurement of the number of kilometers thickness of sediment in the center of a large basin presents a problem which cannot be solved even partially by any geophysical method up until now. The magneto-telluric method should be able to solve the problem by use of only a single station.

The discarding of the base station, which is indispensable in the telluric method, gives the operator more freedom of movement and improves the organization of his survey. He is no longer compelled to proceed slowly. He can afford to operate in a more rational way by setting up his initial stations at some distance from each other. Later on, he can locate stations with a closer spacing, but only to the extent required by continuity.

Consequently, one can lay out the survey of a large sedimentary basin by performing at the start a small number of MT-soundings far removed from one another, but with a great depth of investigation. In the second step, one will intercalate stations closer together, and at these he will perform MT-soundings with a more moderate depth of penetration. Finally, the continuity between the stations will be assured either by soundings with a relatively small depth of investigation, or, once in a while, by simple, quick determinations of the apparent resistivity summarily evaluated through a very simplified analysis of the magneto-telluric data. It is unnecessary to add that the magneto-telluric method will be particularly appreciated every time that a deep petroliferous structure

appears in complete disharmony with the structure on the surface. In this case it is essential for the prospector to penetrate to a great depth of investigation.

If it should happen that the earth is not even approximately stratified, the quantitative interpretation of the MT-soundings must be just about ruled out. A knowledge of the apparent resistivities and of their variation as a function of the period and of the direction of the line provides, nevertheless, certain indications which can be diagnostic in special cases, even though they are to a large degree qualitative.

ACKNOWLEDGMENTS

I am very glad to express my heartiest thanks to Mrs. F. B. Riek, Jr., to Dr. Robert Van Nostrand, Dr. Milton B. Dobrin and Dr. R. L. Caldwell, Field Research Laboratories, Magnolia Petroleum Company, and to Mr. E. Selzer, physicist at the Institut de Physique du Globe of Paris.

Mrs. Riek, a professional translator, undertook the translation of my French text into English for the Magnolia Petroleum Company. Drs. Van Nostrand, Dobrin, and Caldwell edited the translation with competence and judgment. My friend Mr. Selzer gave me valuable help in correction of the proofs.

The theoretical work reported in this paper was done some time ago and has been mentioned in applications for patents which have been made in several countries to protect the new prospecting method involved. Because of the potential practical applications I have had to postpone any publication related to magneto-telluric phenomena for many years.

Meanwhile, the Russian scientist Tikhonov, and the Japanese scientists Kato, Kikuchi and Rikitake had also recognized the existence of such an effect. To my knowledge, they have not pointed out the possibility disclosed by my work of applying these results to practical geophysical exploration. They have, however, paid attention to their possible use for investigating the electrical conductivities of very deep regions in the Earth's crust.

It is therefore a real pleasure for me to give these scientists proper credit and to list the papers that, to my knowledge, they have published on this subject:

Kato, Y. and Kikuchi, T. (1950) *Sci. Rep. Tôhoku Univ. Ser. V, Geophysics*, Vol. 2, p. 139.

Rikitake, T. (1950) *Bull. Earthquake Res., Inst. Tokyo Univ.*, Vol. 28, p. 45, 219. Also (1951) Vol. 29, pp. 61, 271.

Tikhonov, A. N. (1950) *Dokl. Akad. Nauk S.S.S.R.* 73, 295.

INDUCED POLARIZATION: A METHOD OF GEOPHYSICAL PROSPECTING*

D. F. BLEIL†

ABSTRACT

Laboratory experiments have shown certain fundamental relationships concerning the induction of a polarization potential on a metallic body in an electrolyte. The potential induced is a linear function of the potential drop across the body in the energizing field up to a saturation potential of 1.2 volts. Diffusion of ions and chemical action are the predominant factors which determine the rate of growth or decay of the polarization potential. Polarization occurs only at the boundaries of electrically conducting minerals. The results of the laboratory experiments provide an explanation of the induced polarization potential of a homogeneous, uniformly mineralized earth. This potential falls off as 1/r from a point electrode. Induced polarization susceptibility is defined and a method of analyzing field data is described. Field measurements over two mineralized zones (pyrrhotite and magnetite) substantiate the theory as developed.

INTRODUCTION

It has long been known that both the anode and the cathode of an electrolytic cell become polarized upon the passage of an electrical current through the cell. This effect provides a means of detecting metallic minerals in the earth either in the form of solid ore bodies or as disseminated particles and forms the basis for the induced polarization (IP) method of geophysical prospecting. Simply, it consists of first inducing polarization on a metallic mass and subsequently detecting that polarization and is accomplished by the procedure illustrated in Figure 1. A metallic mass M is surrounded by a rock matrix having interstices filled with an electrolyte. The presence of the mass will distort the current flow in a manner governed by the relative resistivity of the metal and the surrounding rock. The surface along which the current filaments enter the mass corresponds to the cathode of an equivalent electrolytic cell, and the surface where they leave to the anode. The metal itself is then the ordinary external circuit. A direct current flowing from electrode A to electrode B will polarize the mass positive on the side where the current enters and negative where it leaves. If the current from A to B is interrupted, the dipole on the mass will dissipate itself by sending a current through the surrounding medium. The recorder R will indicate the ohmic drop between the points C and D caused by this polarization current. To avoid measuring the ohmic drop caused by the energizing current, one keeps switch S open until the current circuit is interrupted.

A number of prospecting methods based on the principle of induced polarization have been investigated and a variety of claims has resulted. Schlumberger (1912, 1920, 1930 loc. cit.) patented a method of prospecting by induced polariza-

* Based on a Ph.D. thesis submitted to Michigan State College. Presented at the Annual Meeting of the Society, Denver, Colorado, April 26, 1948.

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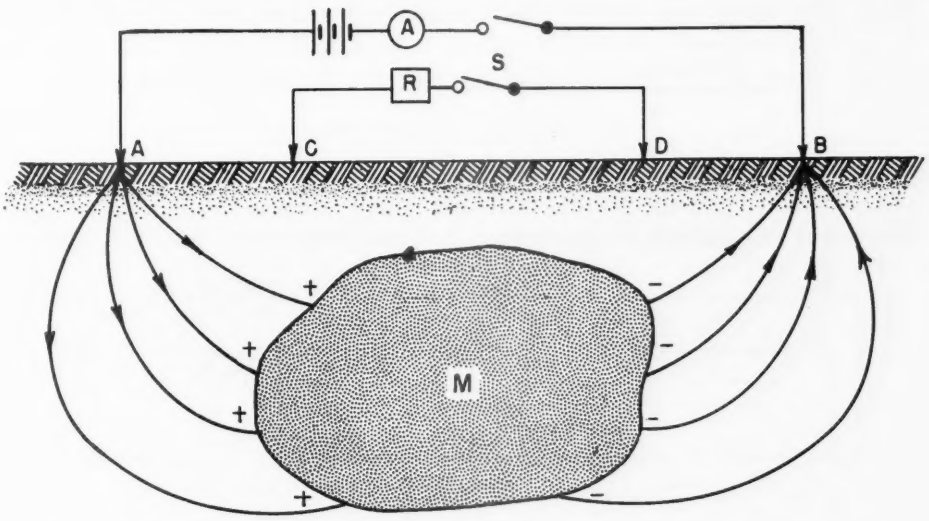

FIG. 1. Current filaments from A to B enter metallic mass M and polarize it. Recorder R measures decaying induced polarization after interruption of energizing current.

tion in 1912 but later admitted that his experiments in the field were unsuccessful. He attributed this failure to such factors as spontaneous polarization, "residual" polarization, ion transportation and the resistivity of the medium. Müller (1932, 1934a, 1934b, 1940) and Weiss (1933) have described a method by which they claim to have obtained information from depths of 3,000 to 6,000 feet with the expenditure of only 1 to 2 watts. Belluigi (1935, 1941), on the other hand, has been unable to duplicate their results. He found their method applicable only to very shallow depths.

A method for the direct detection of oil, which employs apparatus similar to that used in the present work, is claimed by Potapenko (1940) and Peterson (1940). It is based on the differences between the polarization effects in electrolytes and in oil.

In addition to the above-mentioned methods, which specifically measure induced polarization, there are several related schemes which measure the electrical properties of the earth. In general, these methods involve measurement of capacitive reactance, which in turn is sensitive to polarization effects. For a discussion of these methods the reader is referred to Blau (1933) Schlumberger (1932), Hawley (1938), Matsubara (1939), Evjen (1945, 1948), and Lewis (1945, 1948).

The research to be discussed in the present paper has been conducted with the object of determining the role of each of the factors which influence polarization. If this were known the interpretation of field measurements would be greatly facilitated. The first part of the project consisted of laboratory experiments designed to control and investigate independently each of the influencing factors

along with theoretical studies which might make these results applicable to prospecting. In the second part, the results of the experiments were applied to the interpretation of field measurements made on two known mineral deposits.

LABORATORY INVESTIGATION

The laboratory experiments were so designed that the effect of each factor (e.g., resistivity, current density, etc.) that might influence the induced polarization would be observed independently. The interpretation of the field measure-

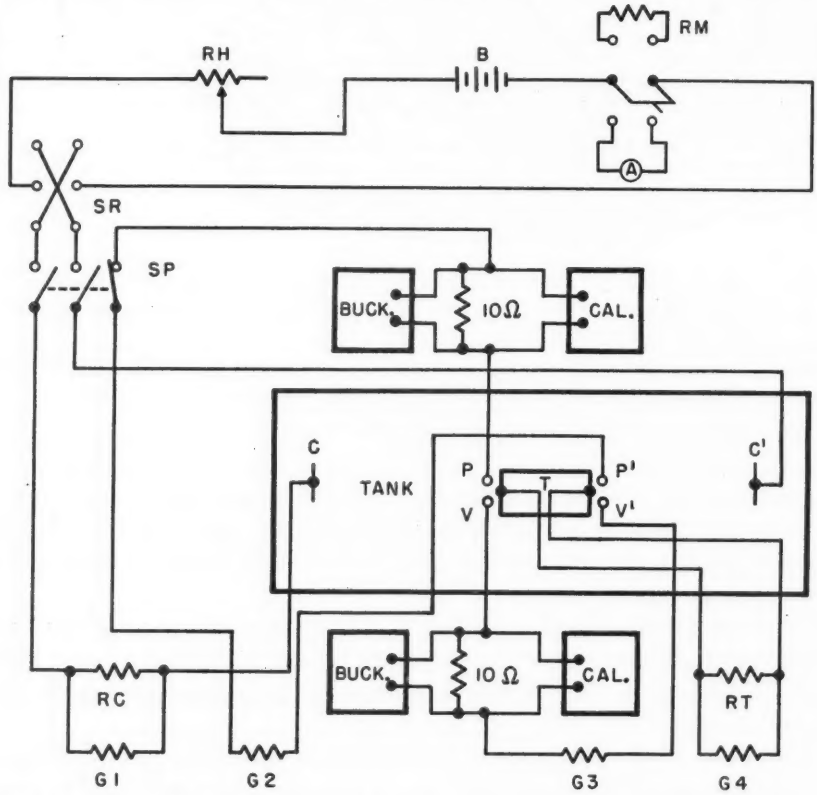

FIG. 2. Diagram of laboratory set-up showing water tank, target and electrical circuit.

ments depends to a large extent on the laboratory results, which will, accordingly, be discussed in some detail.

Experimental Procedure

The first model to simulate the earth consisted of clean quartz sand in a wooden tank. It was soon established, however, that the same results could be obtained in a tank filled with water and this was used for most of the experiments. The resistivity was adjusted to the desired value by adding the proper

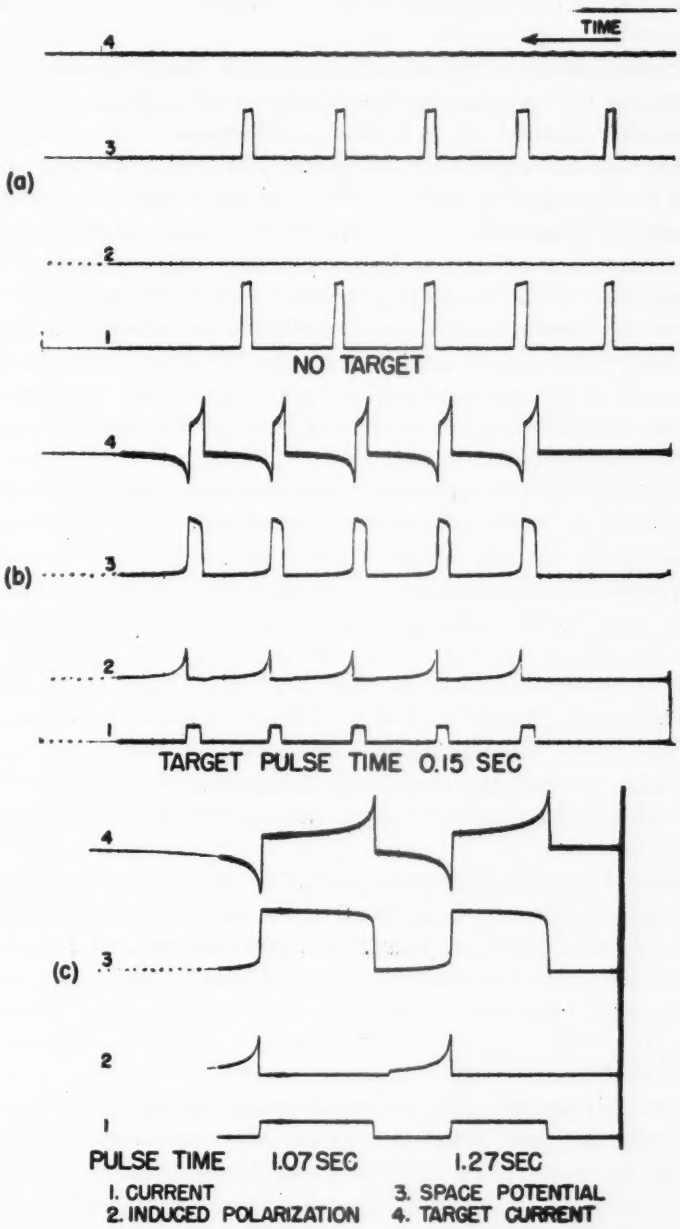

FIG. 3. Typical oscillograph record. Record (a) shows results obtained without a target. Records (b) and (c) were obtained with target in place. Trace 1 shows the energizing current pulse, Trace 2 the induced polarization potential, Trace 3 the potential across target space, and Trace 4 the current through target.

amount of salt (NaCl) to the water. The concentration of the NaCl varied from 0 to 3.6 percent by weight.

The electrical circuit of the recording system is shown schematically in Figure 2. Electrodes CC' supplied the energizing current, which was measured by the galvanometer element G_1 of a Shell oscillograph. This current was alternately started and interrupted by the pulsing switch SP. When the current was interrupted, the Ag/AgCl electrodes (PP') were simultaneously connected across the galvanometer element G_2, which recorded the decay of the polarization potential. The switching mechanism prevented the energizing-current circuit and the polarization-potential circuit from being closed at the same time. Ten milliseconds after the current circuit was interrupted the polarization potential circuit was completed. A second pair of electrodes VV' gave a continuous measure of the potential in the space outside the polarizable body. The electrodes PP' and VV' were shielded from the energizing current. Provision was made for the calibration of both potential circuits.

A variety of polarizable bodies (targets) was investigated. The one most frequently used was a plastic tube 20 cm long with end caps made of thin sheet iron approximately 100 cm^2 in area. This is represented by T in the diagram. Wires were soldered to the insides of the iron plates and brought out through a tube in the center of the cylinder. The end plates were pressed into the tube and the whole cylinder was filled with a potting compound which kept the water out and also added weight. The two wires leading out from the target were connected to the galvanometer G_4. The two end plates were thus connected electrically and the target was essentially a solid metallic body. The fact that the current passing through the target was measurable in terms of the potential across RT made this target particularly desirable for investigating induced polarization.

A number of typical oscillograms obtained with the above equipment are shown in Figure 3. Trace 1 is a record of the energizing current given by G_1; Trace 2 the decaying induced polarization potential measured by G_2; Trace 3 the potential exterior to the target, measured by G_3; and Trace 4 the current through the target, measured by G_4.

Existence of Induced Polarization

With the instruments connected as shown in Figure 2, measurements were first made with no target between the electrodes. The target was then inserted between the electrodes (PP' and VV') and the measurements were repeated. The traces obtained are shown in Figure 3, where (a) was obtained for the no target run and (*b*) and (*c*) with the target in place. In (*a*) Trace 1 gives both the magnitude and shape of the energizing current and Trace 3 the potential across the target space. The sensitivity of the recorder element which produced Trace 2 on the no-target record was so adjusted that a potential of 25μ volt would

give a deflection of 1 mm. This element, however, showed no deflection. Results were the same when the medium employed was sand saturated with salt water. It was thus demonstrated that no polarization potential is observable in clean quartz sand or water (salt or fresh). The situation, however, was greatly altered when a piece of metal was introduced between the electrodes. Records (b) and (c) show the results obtained when the target, with iron plates, was placed between the electrodes. The most significant feature of these two records is the potential decay indicated on Trace 2. The signals on this trace were obtained entirely after the termination of the current pulse. They represent potentials arising from the polarization induced at the target boundary. Further, the current through the target (Trace 4) also demonstrates the existence of the polarization potential. At the initiation of the energizing pulse, the faces of the target acted as electrodes and current passed through the target. Upon the development of polarization at the target faces, the target current was decreased. The longer the pulse duration, the greater the decrease of the target current until a steady residual current was established when equilibrium was reached between the rates of formation and escape of electromotively active material. When the energizing current was interrupted, the electrolytic cell, formed by the products of polarization, discharged itself through the surrounding medium. The current entering the medium by this discharge is shown as the reverse current through the target.

Induced Polarization and the Energizing Potential

The relationship of the induced polarization to the energizing current was obtained for a given model by varying the energizing current and observing the corresponding polarization potential. Figure 4 shows plots of the IP potential, the space potential for no target, and the space potential with target, as functions of the energizing current. With no target in place, the potential across the target space obeys Ohm's law. With a target, however, the space potential is larger than the value given by Ohm's law up to the crossover point at approximately 1.2 volts. Beyond this, the potential falls below its ohmic value. The induced polarization potential is also a linear function of the energizing current, or more exactly the potential drop across the target, up to 1.2 volts and this linearity is independent of the resistivity of the medium. Moreover, the IP curves obtained in electrolytes of different resistivities and with various target metals all pass through the origin. This indicates that no threshold of potential is required to establish polarization effects. In addition, all curves show a saturation effect at approximately 1.2 volts (the fact that the theoretical value of the hydrogen-oxygen cell is 1.23 volts may have significance in this case).

There is another saturation effect, which can be seen in Figure 3. It depends on the length of the applied current pulse. If the length is increased, the magnitude of the IP potential increases until saturation is reached. The rate at which the saturation value is approached depends on the resistivity of the electrolyte.

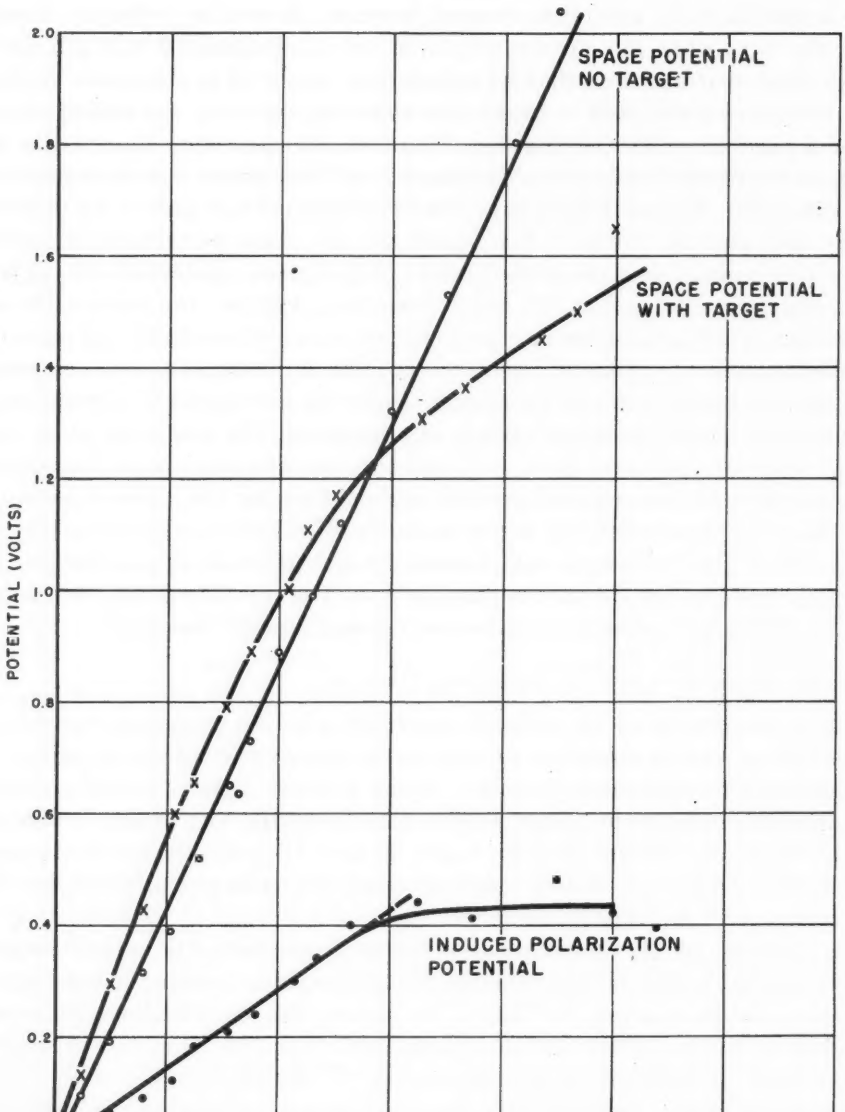

FIG. 4. Potential across the target space without a target, potential across the target space with a target present, and induced polarization potential, all plotted as function of energizing current.

Induced Polarization and the Matrix Resistivity

The resistivity of the surrounding medium enters into the induced polarization of a body in several ways:

1. As shown earlier, the polarization potential is a linear function of the po-

tential drop and, therefore, proportional to the resistivity of the medium. Thus, in prospecting, the resistivity of the matrix will have a pronounced effect. This will have to be measured in any field determination of induced polarization.

2. Laboratory measurements have revealed that the polarization potential developed is directly proportional to the initial current entering the target. Obviously, the initial current through the target depends on the ratio of the resistivities of the target and the surrounding medium. A saturation of the polarization has been found to occur when the target resistivity is less than one-tenth that of the matrix. The mineral will be only slightly polarized if its resistivity is greater than that of the matrix. Little is gained, on the other hand, if the resistivity of the matrix is greater than 10 times that of the mineral.

Decay Time of the Induced Polarization

Since the polarization is dissipated through the surrounding medium, the rate of decay will depend to some extent on the resistivity of that medium. A number of decay and growth curves were measured as a function of the resistivity of the electrolyte. All the curves obtained show a marked similarity. None of these decay curves, however, have the exponential form indicating a purely resistive discharge. Hence, some factors other than the resistivity must contribute to the rate of discharge of the polarization. Three differential equations are given in the literature for the discharge of the products of polarization from electrodes. These are shown in the first column of Table 1. The second column gives the solutions of the equations.

TABLE 1

Rate of Decay	Potential vs time	Remarks
(*a*) $dE/dt=-Ae^{kE}$	$E=B-(1/k)\ln(t+c)$	Bowden and Rideal (1928)
(*b*) $dC/dt=-kE^2$	$E=\frac{A}{(t+C)}$	Usually assumed
(*c*) $dE/dt=-\beta E$	$E=E_0e^{-\beta t}$	Ordinary exponential

Equations (*a*) and (*b*) pertain to a conventional electrolytic cell and represent the discharge of the active electrode material when no electric current flows through the external circuit. The electrodes formed by the target faces in the experiments on induced polarization were always connected. This arrangement violated the condition of zero current required by equations (*a*) and (*b*). Thus, agreement between the actual discharge curves and either of the first two potential-time functions listed in Table 1 should indicate that the resistivity of the medium is less important in determining the decay characteristics than the open-circuit discharge of the polarization products. All the decay curves obtained in the laboratory fit equation (*b*) over the range of the data available. It is concluded therefore, that the decay of the induced polarization potential with time is governed mainly by ion diffusion and chemical action at the polarized surfaces and

is nearly independent of the resistivity of the surrounding medium. It follows that variations in the resistivity of the earth from place to place can have little influence on the form of the decay curves obtained. Hence, two discharge curves obtained at different places on the earth may be compared at corresponding times.

The decay time-constant of the IP potentials is about 0.3 second. This time is approximately a thousandfold greater than the value given by the RC time constant of the earth (Pearson, 1934) and the polarization decay will not, therefore, be affected by this constant. Actually, the delay time of the pulsing switch used was long enough for the ordinary RC transient effects to have expired.

Behavior at Chemical Boundaries

Müller, Weiss, Potapenko and others have expressed the belief that a polarization potential can be induced at a chemical boundary, i.e., a boundary separating regions having chemically different electrolytes. They have shown that a high degree of correspondence should be expected between the chemical boundaries and formation boundaries. The laboratory experiments described above do not admit a mechanism for inducing polarization at a boundary which does not have electrically conducting minerals on one side. However, this effect was investigated with a cell containing a different electrolyte than the surrounding medium. The two electrolytes were separated by vegetable-paper diaphragms which closed the ends of the cell. Although a variety of electrolytes were used, no induced polarization potentials were observed for any of the solutions contained in the cell when it was immersed in a medium of low resistivity. A very small potential was observed for both the $CuSO_4$ and NaCl targets, when immersed in tap water. This potential, whatever its origin may be, is a second-order effect compared with the induced polarization potential of iron. It appears unlikely that Müller and Weiss could have observed any effect from such a boundary, certainly not from one at 3,000 feet below the surface.

Concerning Ionic Concentration

Schlumberger has predicted a polarization effect attributable to dissymmetry around the current electrodes caused by transport of ions. To test this prediction, apparatus was designed that would enhance any dissymmetry effect but no potentials caused by dissymmetry were ever detected. It is concluded that any induced potential difference attributable to this effect is either too small to measure (less than 40μ volts) or disappears too rapdily to be measured with the equipment employed. The latter explanation seems to be more likely in view of the relaxation time for salt water, which Stratton (1941) computes to be 2×10^{-10} seconds. Certainly the effect determined by Schlumberger was not that of an induced ionic concentration gradient. The effect may have arisen from some other cause, possibly a uniform dissemination of conducting mineral particles.

Other Factors Influencing the Polarization Potential

One factor influencing polarization which is of importance in prospecting is the composition of the ore body. Targets having end plates of brass, lead and copper were investigated in addition to the usual iron end plates. A clump of magnetite, a clump of pyrrhotite and a carbon rod were also used as target materials. An induced polarization potential has been obtained for every metal investigated and also for the carbon rod. In all cases the measured potentials are comparable to those obtained with iron.

Another factor which can influence the polarization potential is the tandem effect of small disseminated particles. It has been shown that the induced polarization potential is proportional to the potential drop across the particle. Therefore, the current density required to produce saturation is inversely proportional to the length of the mineral particle. The polarization potential (at saturation) measured across two short particles in tandem will be greater than that across one particle of equivalent length. This effect was experimentally verified by measuring the induced polarization potential (at saturation) across each of the two iron bars of different length and then across the combination of two bars in tandem (separated by a $\frac{1}{8}$-inch gap). The potential across the combination continued to increase, exceeding that for a bar equivalent in length to the combination, until saturation was produced across the shorter bar. This tandem effect will serve to accentuate the polarization potential of disseminated minerals, particularly if the particles are well aligned and not widely separated. An increase in the separation of the particles will reduce the polarization potential measured across the combination. The induced polarization potential will therefore be sensitive to the percentage of polarizable minerals contained in the rock.

The predicted polarization of disseminated conducting mineral particles was verified in the laboratory. A volume of clean quartz sand was mixed with iron grit until the metal formed 10 percent by weight of the sample. The sample was imbedded in a matrix of clean quartz sand and investigated with a Wenner electrode system. Figure 5 shows the polarization observed along a profile crossing the zone of dissemination. The results shown in the inset of Figure 5 were obtained by rotating the configuration of electrodes around the center of the zone of disseminated mineral. The polarization potential has its maximum value in the direction of the largest geometrical dimension of the disseminated zone.

Conclusions

The following facts have been established in the laboratory:

(a) A polarization potential can be induced on the surfaces of a metallic object in an electrolyte.

(b) The potential induced is a linear function of the potential gradient until a potential of 1.2 volts has been established across the object. Beyond this potential a saturation effect begins.

(c) Ionic diffusion and chemical action of the products of polarization play

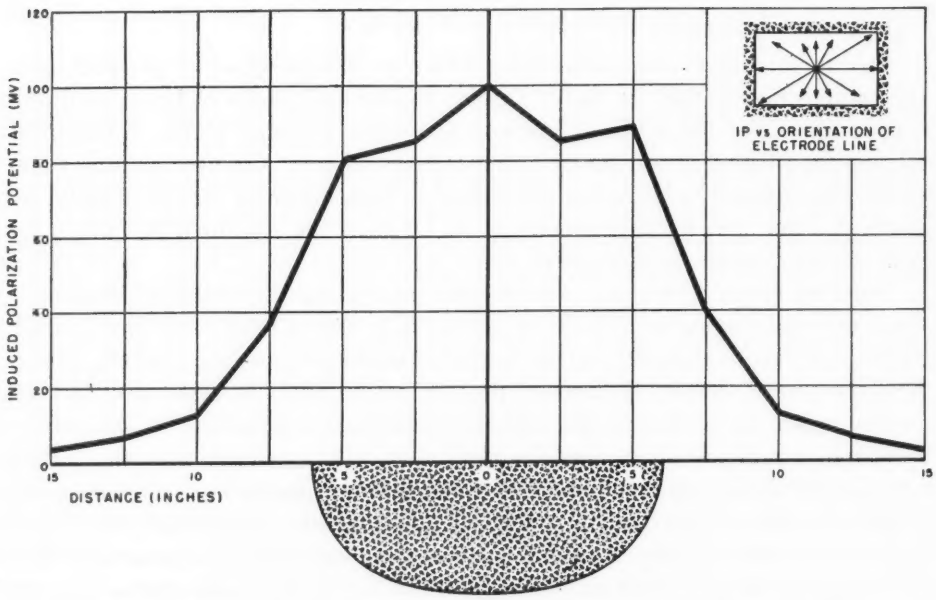

FIG. 5. Induced polarization potential over a zone of disseminated metal in a medium of clean quartz sand. Inset shows results of rotation of electrode system about a fixed center.

the predominant role in determining the rate of growth and decay of the polarization potential.

(d) To a first approximation, only metallic or metal-like bodies are polarizable.

(e) Metallic particles disseminated throughout an unpolarizable matrix are polarizable.

From the foregoing observations, the following conclusions are derived:

(a) Polarization products are induced on a boundary in an electrolyte only when there is a change in the mode of conduction, that is, from ionic to electronic or vice versa.

(b) The charge density induced on the boundary is proportional to the current density component normal to the boundary and is of such a sign as to oppose the current which generates it.

(c) If polarization is induced at all, it is induced upon an electrically conducting mineral which is either disseminated or in a solid ore body.

(d) The current required to produce saturation will be greater for the disseminated mineral than for the solid ore. Moreover, for a given energizing current, the induced polarization potential of a mineralized zone will be smaller when the mineral is encased in a rock of low resistivity than when it is in a rock of higher resistivity. There are two reasons for this: (1) The potential gradient established across the mineral will be smaller and (2) the ratio of the resistivities of matrix and mineral will be decreased.

(e) The shape of the decay curves will be independent, as a first approximation, of the resistivity of the medium surrounding the mineral. The curves, therefore, will have a time constant which will always be approximately the same regardless of the location of the mineral.

It follows that the "residual" polarization potential described by Schlumberger arose from a more or less uniform distribution of electrically conductive minerals. The potentials which Potapenko measured probably had the same origin. None of the claims of Müller and Weiss are tenable in view of the above conclusions. They were probably measuring only the polarization of their own current electrodes, which was many times greater than the effect they sought.

The conclusions resulting from the laboratory experimentation establish some specifications regarding the procedure to be followed in the field and also on the method of reducing the field data. Measurements of the apparent resistivity will have to be taken in conjunction with the polarization data. The resistivity factor must be removed from the measurements obtained in the field before such measurements made at various locations are compared. Because of the linear relation between the energizing current and the induced potential, the field measurements will have to be normalized to a given current. The form of the curve for the decay of the IP potential requires an energizing-current pulse which is not less than 0.3 second in duration if time-saturation is to be reached for a given current. However, the pulse time does not have to exceed 0.5 second. From a consideration of the electrical transient effects it appears that the delay time in the switching cycle may become as small as 10 milliseconds before there is interference from the rapidly decaying ohmic potential.

Theoretical Discussion

Uniformly Mineralized Earth

From the laboratory experiments it becomes a simple matter to obtain an expression for the polarization potential of a uniformly mineralized earth. It is assumed that there is a uniform distribution of metallic minerals and that the resistivity of the medium is also uniform and constant. Under the action of an energizing current from a point electrode at the origin, a unit volume will then become polarized according to the relation

$$P = -c\rho i = -ki$$

where i = current density and ρ is resistivity. The potential ϕ_s at any point on the surface of the earth is then the volume integral of the potentials due to the elementary dipoles. This is given by

$$\phi_s(x, y, z) = \int_V \frac{P \cos \theta dV}{R^2} .$$

where R is the distance from the point to the volume element in question and θ is the angle between the dipole axis and the radius R. These relations are identical

with those obtained in the classical treatment of polarization and we may therefore write down the final result at once. In the notation used here, this becomes

$$\phi_s(x, y) = \frac{kI}{r} \tag{1}$$

where I is the energizing current and r the distance from the source of the current. The maximum induced polarization potential for the uniformly mineralized earth falls off as $1/r$ from a point energizing electrode. This result was verified in the laboratory for a point current electrode in the center of an iron hemisphere filled with a uniformly mineralized sand.

The $1/r$ relation for the uniformly mineralized earth was further substantiated by polarization potential measurements made on limestone in Lebanon County, Pennsylvania. These measurements will be discussed later.

Interpretation of Measurements

The $1/r$ relation for the uniformly mineralized earth leads to a means for interpreting the field measurements. Introducing the resistivity back into equation (1) gives

$$\phi = c\rho I/r.$$

If a Wenner configuration is used the potential takes the familiar form

$$\phi_0 = c\rho I/a,$$

where ϕ_0 represents the maximum difference in potential (at $t=0$) across the potential electrodes. The resistivity for this configuration is

$$\rho = 2\pi a V_0/I_0.$$

A combination of these equations gives

$$c = \phi_0 I_0/2\pi V_0 I = \phi_0/2\pi V_0, \tag{2}$$

when the current flow I_0, which produces the ohmic potential V_0, is taken to be the same as the value of the energizing current I, which produces the induced polarization potential ϕ_0. Designating $2\pi c$ as S, we get

$$S = \phi_0/V_0 \text{ mv/volt}. \tag{3}$$

The quantity S may be defined as the induced polarization susceptibility and this may be regarded as a property of the volume under investigation. It is this quantity which is determined in a field survey. The ratio of the two potentials should actually be a dimensionless quantity, but for convenience the values of ϕ_0 have been expressed in millivolts whereas those of V_0 are in volts. It is to point out the discrepancy in the magnitudes of the two quantities that the pseudo-dimension millivolt/volt has been appended to the susceptibility constant S.

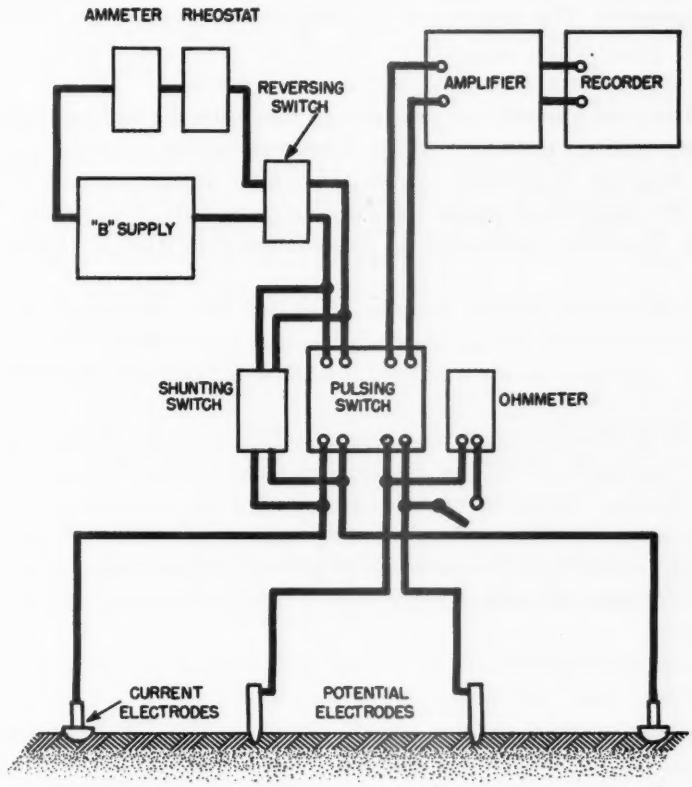

FIG. 6. Block diagram of field equipment.

The field apparatus could not, unfortunately, always measure both ϕ_0 and V_0 for the same current. One intentional feature in the design of the field apparatus which precludes the direct application of equation (3) is the delay time in the switching cycle. The IP potential at zero time cannot be measured directly and in the case of the field results to be considered here, this quantity was obtained by extrapolation of the observed potentials back to zero time. This extrapolation is safe since the decay curves fit a known form. The decay curves obtained in the field were observed to fit the E^2 relation for the rate of decay acceptably well and the values of ϕ_0 have been obtained from the equation

$$\phi = A/(t + c),$$

where ϕ is the difference of potential measured at the surface of the earth.

FIELD SURVEY RESULTS

Instrumentation

The instruments used for the laboratory experiments were unsatisfactory in the field. Figure 6 shows a block diagram of the instruments as redesigned for the

field measurements. The equipment was designed to measure the resistivity and the induced polarization separately. Except for the input circuit and pulsing mechanism, commercial recording instruments were used.

The pulsing mechanism was designed to maintain the leakage resistance between the energizing current circuit and the polarization potential circuit in excess of one megohm. A resistance-capacitance filter of the "parallel-T" type was inserted in the input to minimize the spurious potentials arising from the 60 cps power lines. The filter introduced an insignificant distortion in the decaying IP signals.

Several additional features were incorporated for convenience of operation. One was a marking pen which indicated the onset and termination of the current pulse. Also, a bucking circuit was helpful when spontaneous polarization was encountered.

Steel rods were satisfactory as current electrodes provided that the electrode separation exceeded 10 feet. The potential electrodes were of the Cu-$CuSO_4$ type and were shielded from the polarizing action of the energizing current. The shielding was accomplished by surrounding the copper electrode with a material of such high resistivity that the energizing current was unable to pass directly through the copper electrode. Porous pots placed on the surface of the earth are quite suitable.

The principal requirements which the field instruments have to satisfy are:

a. To effect, in a non-overlapping sequence, the opening of the potential circuit, the closing of the energizing current circuit sending a known step pulse into the ground, the opening of the current pulse circuit, and the closing of the potential circuit. The potential electrode circuit must not close before the current electrode circuit has opened but must close with a uniform time delay after the opening of the current circuit.

b. The electrical constants in the potential circuit must be such that an exponential decay signal with a time constant of 25 milliseconds can be passed without distortion.

c. The filter must attenuate the background disturbance to a fraction of a millivolt.

The pulsing circuit used was essentially an on-off switch in the energizing circuit which gave a current pulse that was roughly square. The magnitude of this pulse depended upon the resistivity of the area and the voltage supply available. Although the magnitude of the current is not critical because it is removed in the final analysis, the pulse was usually of the order of $\frac{1}{4}$ to $\frac{1}{2}$ ampere; on occasion it was as much as one ampere.

After the operational characteristics of the equipment had been established, two preliminary surveys were conducted to test the induced polarization method of prospecting. These surveys were conducted over areas where sharp boundaries separate zones of good electrically conducting minerals from poor conductors.[1]

[1] The locations were suggested by the U. S. Geological Survey.

The two surveys are briefly described and then measurements made over both pyrrhotite and magnetite deposits will be discussed.

Measurements over an Amphibolite Dike

The first survey was over an amphibolite (meta-basalt) dike which was exposed in a road cut. The dike cuts through a knoll of Wissahickon schist a little off the knoll's center, dipping to the east at an angle of about 60° with a strike of roughly N20°E. It is about 50 feet wide on the north side of the road and nearly 60 feet wide on the south. Except for the road cut in the knoll, the topography fails to reveal the dike.

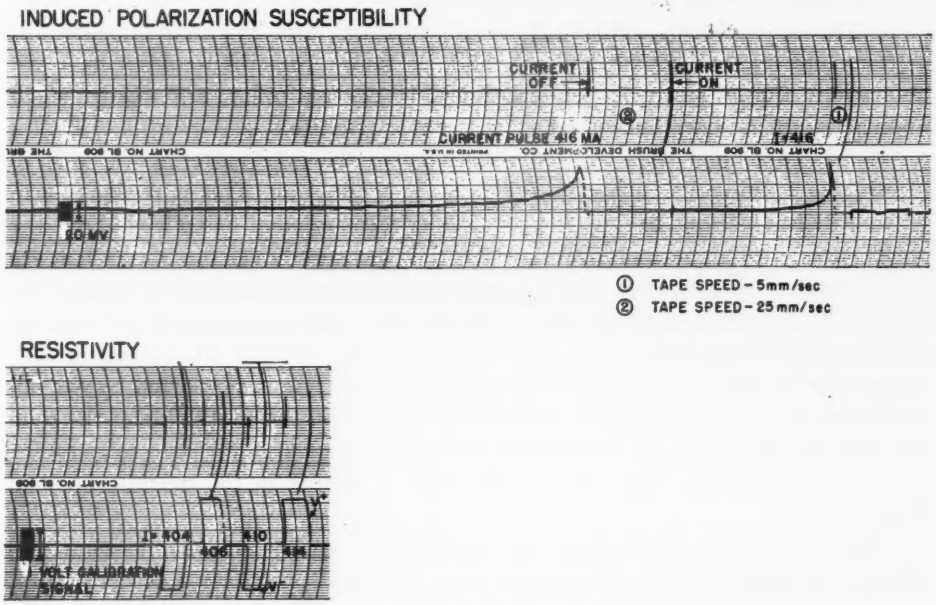

FIG. 7. Typical field records.

Measurements were made along three traverses parallel to the road and 175 ft. apart. Each measurement for which the electrode separation remained constant will be designated here as a run. Unless otherwise indicated, the distance moved along the traverse from station to station in a given run was equal to the electrode separation. A Wenner configuration was used for all three traverses; the electrode separation a was equal to 20 feet. At each station several current pulses were delivered to the earth in each direction and the resulting IP potential was recorded. Six d-c resistivity measurements were also made, the polarity being reversed between successive measurements. Sections of recorder tape showing both types of measurement are reproduced in Figure 7.

The resistivity as measured along Traverse 1 was high (0.12 megohm-cm) over the Wissahickon but dropped to 0.02 megohm-cm over the dike. However, the dike was not revealed by the resistivity measurements along the two subse-

quent traverses. The normalized IP measurement (without the resistivity factor removed) showed excellent correlation with the resistivity curve as predicted. When the IP measurements were treated in the manner previously outlined, using equation (3) to compute S, the correlation disappeared. The IP susceptibility curve indicated a higher mineralization in the Wissahickon northwest of the dike and a lower value over the dike. Magnetometer readings were taken along all three traverses. They, too, indicated the largest anomaly along Traverse 1 and at the place where the larger IP susceptibility values occurred. On the other hand, the location of the dike was not revealed by either the IP susceptibility curve or the vertical magnetic field readings.

The dike material gave an electron diffraction pattern which matched that of nontronite ($FeOSiO_2 \cdot 2H_2O$);[2] it was hygroscopic and was found to contain 0.36 percent magnetite. A sample of the mica schist from the road cut near the area where the larger values of resistivity, IP susceptibility, and vertical-field anomaly were obtained contained 3.3 per cent magnetite.

It was concluded that the low resistivity of the dike material was due to electrolytic conduction rather than electronic conduction. This is reasonable in view of its hygroscopic nature, the zone under measurement being well above the water table. The higher polarization potentials measured over the mica schist are interpreted as coming from the higher concentration of magnetite. Neither the resistivity, magnetic or IP methods revealed the existence of the dike beyond the first traverse. These observations force the conclusion that the dike tapers out and disappears on the north side of the road. This conclusion is supported by the observation that the dike is wider where it is exposed on the south side of the road cut than on the north side. If straight lines are drawn across the road so as to line up with the exposed edges of the dike, they converge in the neighborhood of Traverse 2.

The conclusions drawn from the amphibolite survey are: (1) disseminated conducting minerals may yield rather large values of polarization susceptibility; and (2) bodies which are good conductors because of the presence of electrolytes rather than of conducting minerals are not polarizable.

Measurements across a Fault between the Wissahickon Schist and the Manassas Sandstone

The correlation of the polarization susceptibility with the magnetic analysis obtained in Traverse 1 suggested that the method might be used to detect faults where the change in resistivity is not pronounced and where a change in the concentration of conducting minerals occurs. It was believed that a fault of this type exists near Manassas, Virginia, where the Wissahickon, known to contain variable amounts of magnetite, has pushed up against the Manassas sandstone.[3] Induced polarization and resistivity measurements were made along three traverses

[2] This information was supplied by Mr. C. Lufcy, Naval Ordnance Laboratory.

[3] C. Milton, Geologist, U. S. Geological Survey, personal communication.

roughly perpendicular to the fault and each 200 feet apart. A Wenner system of electrodes in which "*a*" was equal to 20 feet was again employed. Samples of earth were taken from a road cut at 25, 50, 75, 100, and 150 feet in each direction from the exposed fault.

The resistivity data showed a definite correlation from traverse to traverse. A change from low to high resistivity was found to fall along the probable strike. Little correlation from traverse to traverse was found in the IP susceptibility curves. An analysis of magnetic minerals in the samples from the road cut indicated that there was more variation in the magnetic mineral content within both the sandstone and mica schist than there was from one to the other.

It was concluded from this survey that the IP susceptibility measurements did not locate this fault because there was an insufficient change in the conducting mineral content from one formation to the other. This conclusion was supported by the magnetic mineral analysis.

Measurements over a Pyrrhotite Outcrop

Polarization experiments were conducted over two ore bodies suggested and described by the U. S. Geological Survey. The first of these, in Carroll County, Virginia, is designated as the Gossan Lead (Wright & Raman, 1948). The Gossan Lead consists of a series of elongated sulphide ore bodies of which the primary ore is pyrrhotite. The mineralized zone is encased in the pre-Cambrian Lynchburg gneiss. The ore in the Cranberry segment outcrops along U. S. Highway 52 near Hillsville, Virginia for a distance of approximately 200 feet. The "float" found along the outcrop was rather massive pyrrhotite. When a piece of ore with freshly exposed faces was connected to the leads of an ohmmeter, the meter read zero on the 1-ohm scale.

Two traverses were run across this outcrop: one along the shoulder of the road and the second one parallel to the first, 20 feet northeast of the road and about 12 feet above the road level. The second traverse ran only across the west contact of the mineralized zone because the hillside was steep, covered with the dump of an old pit, and heavily overgrown. A Wenner system for which *a* was 20 feet was used to obtain the data of Traverse 1, Run 1 and Traverse 2, Run 1. The results of these two runs, plotted in Figure 8, show the induced polarization susceptibility increasing to a maximum as the contact is approached from the side of the country rock. Once the contact is crossed, the polarization susceptibility appears to fall to zero. However, it is the induced polarization potential which has fallen to zero (or at least below the lower limit of the instrument sensitivity). The fact that this potential disappears over the pyrrhotite zone should make the susceptibility also zero except for the fact that the ohmic potential also falls to zero there. Since the susceptibility is the ratio of these two potentials, it is therefore indeterminate over the mineralized zone. The zero value of the induced polarization potential is, however, in excellent agreement with the basic rule which states that the polarization potential is proportional to the potential gradient.

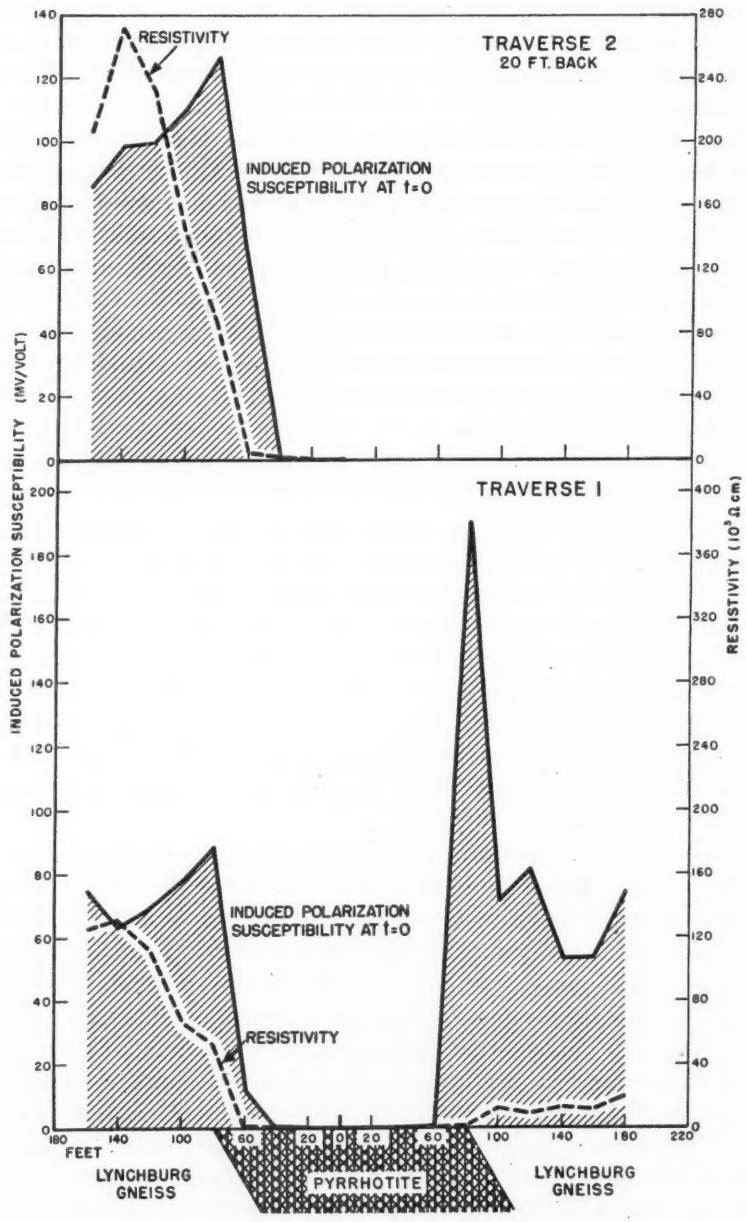

FIG. 8. IP susceptibility and resistivity over Cranberry segment of the Gossan Lead (pyrrhotite) as a function of distance along segment.

Even when the current was increased to 1.0 ampere, the resistivity remained zero as far as the field instruments could give readings, and therefore the potential gradient and consequently the induced polarization potential were still zero.

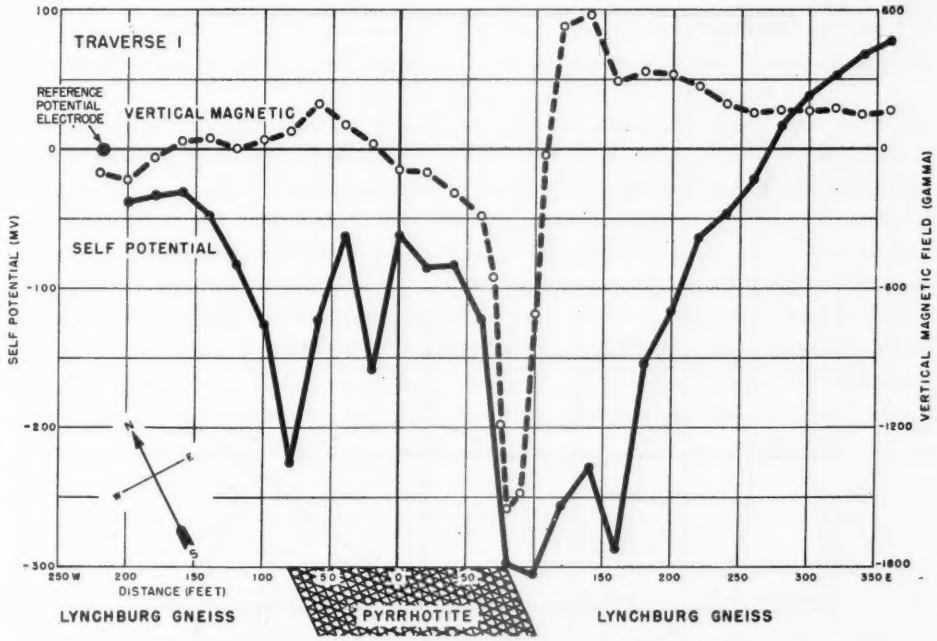

FIG. 9. Self-potential and vertical magnetic-field over Cranberry segment.

Pyrrhotite is known to display self- (spontaneous-) polarization. Schlumberger (1930) has stated that the spontaneous polarization of an ore body would conceal the induced polarization potential. To check this prediction, measurements were made of the self-potential over the Cranberry segment. The reference electrode was located 220 feet west of the center of the ore body and the potential difference between it and the probe electrode was recorded as the probe was moved across the ore body at 20-foot intervals. These data are plotted in Figure 9 along with readings of the vertical magnetic field measurements taken along the same traverse. The ore body shows definite spontaneous polarization but the self-potential does not influence the induced polarization potential. Although the energizing current was pulsed in both directions, no change in the magnitude of the induced polarization potential was observed. It was necessary, however, to use large bucking potentials to keep the recorder pen in the center of the paper.

Measurements over A Magnetite Ore Body

The second ore body, wedged between a limestone and diabase contact, was one of the many small magnetite deposits found in Lebanon County, Pennsylvania. Fortunately the area had been explored and the data from six diamond-drill holes (DDH) were available. The projection onto the horizontal plane of the probable limit of the ore body is shown in Figure 10. The strike of the ore body is along an east-west line and it dips to the south at an angle of about 60°.

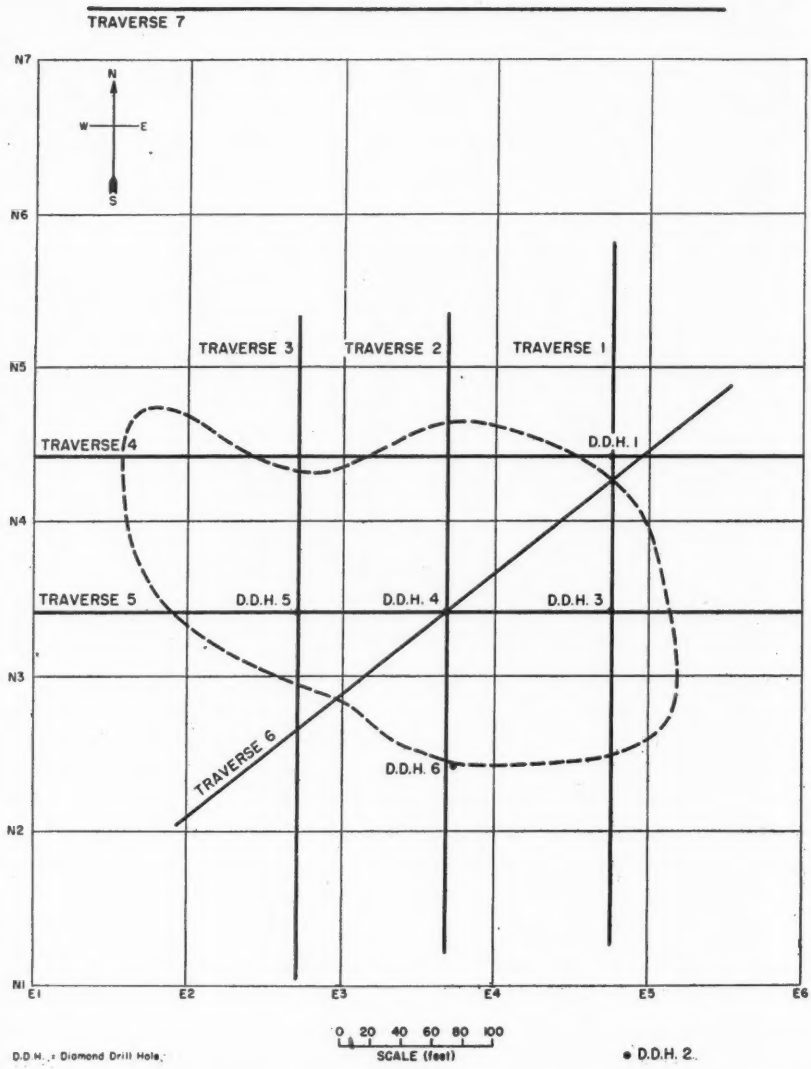

FIG. 10. Horizontal projection of probable limit of a magnetite deposit, Lebanon County, Pennsylvania, showing traverses along which measurements were made.

The nearest approach to the surface is at a depth of approximately 25 feet and its maximum thickness, which is along Traverse 2, is about 60 feet, occurring roughly 50 feet below the surface. Seven traverses (see Figure 10) were conducted in the area; six of the seven were over the probable ore body and the seventh was removed from it intentionally.

Traverses 1, 2 and 3 were run roughly parallel to one another in the north-south direction and spaced to cross the existing drill holes. Two runs were com-

pleted along these three traverses: Run 1, for which a was 50 feet, and Run 2, for which a was 100 feet. The stations for both of these runs were taken at 25-foot intervals.

The induced polarization susceptibility and the resistivity have been reduced, in the manner outlined previously, for Run 1 of Traverses 1, 2 and 3. Figure 11 is an areal map of the IP susceptibilities obtained from this run for the three traverses. On these maps, areas where the signals are 50 millivolts/volt or more are shaded black. Intervals between 5 millivolt/volt contour lines are shaded so that each interval is lighter as the signal decreases. The magnitude of the polarization susceptibility of the limestone appears to be rather small and it maintains a uniform value of about 20 millivolts/volt. As the magnetite is approached from the limestone, the susceptibility constantly increases. The largest value occurs along Traverse 2 where the ore is thickest. The double peak observed along

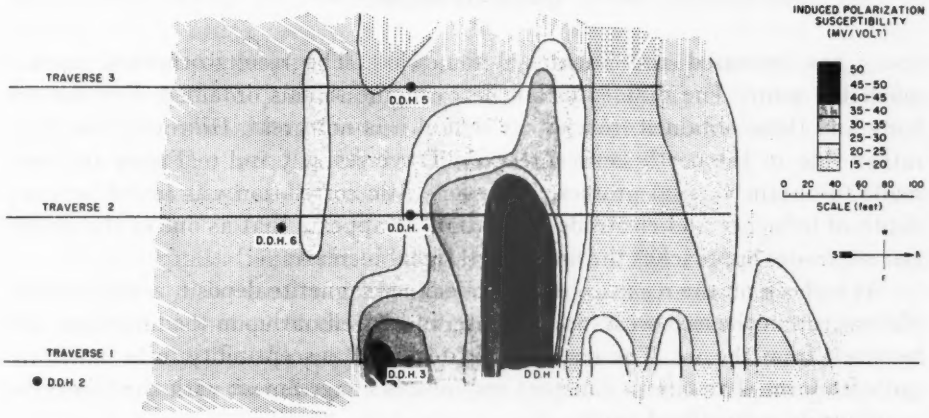

FIG. 11. Areal map of the IP susceptibility measured along Traverses 1, 2 and 3. A Wenner system was used for which a was 50 feet.

Traverse 1 is of interest. The first peak occurs over the top of the ore (at its shallowest depth) and the second is just south of DDH-3 where the ore is thought to be about 131 feet deep. The resistivity showed a small dip at the same place. In addition to the IP susceptibility and resistivity measurements, vertical magnetic-field readings were also taken along Traverses 1, 2 and 3. An anomaly in the vertical-field measurements which is as large as the largest value measured along Traverse 3 occurs at the same location as the second peak in the IP curve. There is certainly a well-localized conducting body just south of DDH-3 which is not revealed by the existing drill holes. The IP susceptibility curves and the vertical magnetic-field data both point to Traverse 2 as the location of the largest amount of ore. On the other hand, little difference was noted in the resistivity data from the three traverses. Run 2, for which a is 100 ft, of Traverses 1, 2 and 3 shows (Figure 12) essentially the same information as does Figure 11. The double peak of Traverse 1 has practically disappeared and the peak along Trav-

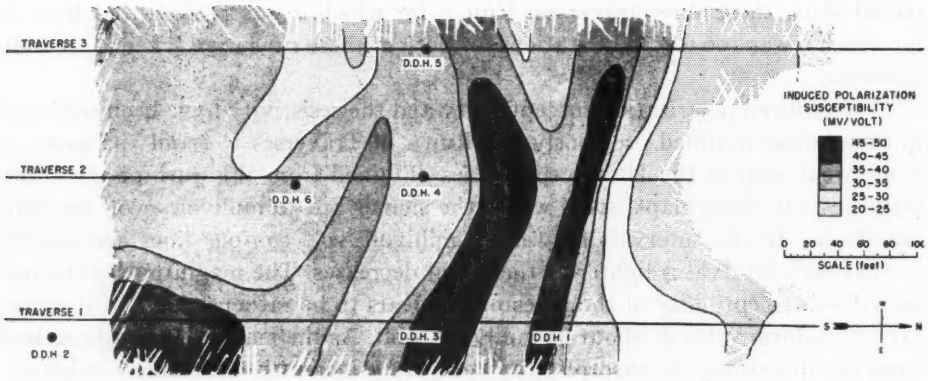

FIG. 12. Areal map of the IP susceptibility measured along Traverses 1, 2, and 3 with an electrode spacing a of 100 feet.

erse 3 has increased and broadened somewhat. The results otherwise appear much the same. The differentiation between the signals obtained over the ore body and those obtained from either side of it is not great. However, the ore is rather thin in the north-south direction. Traverses 4, 5 and 6 (Figure 10) were made to obtain vertical profiles. However, little correlation was found between depth of influence and electrode separation. It appears that as one of the potential electrodes approaches the ore, the IP signal increases.

As a check on the results obtained over the magnetite deposit, a vertical profile was run in the east-west direction at a place well out upon the limestone and removed from the ore. The results indicate the IP susceptibility to be small and quite uniform. The almost constant response is in agreement with the theory for a uniformly mineralized earth.

Data obtained from the vertical profiles (Traverses 4, 5 and 6) are still useful even though the desired correlation of depth with electrode separation is not apparent. Over DDH-4 at an electrode separation of 100 feet, there are three values of the IP susceptibility: Traverse 2, Run 2 in the north-south direction, Traverse 5 and Traverse 6. When the results from these three stations are compared, it is found that the largest value came from Traverse 5 and the smallest from Traverse 2. The value from Traverse 6 was intermediate. The IP potential should increase in magnitude as the length of the polarizable body is increased because it is essentially a dipole source. Thus, measurements made in several directions over a non-spherical body will generate an "ellipse" of polarization with its major axis in the direction of the strike. The results of the three traverses above bear out this effect.

A survey was conducted in which the electrodes were separated by 50, 100 and 150 feet for each orientation of the electrode line and the line was rotated about its center into six positions. This procedure was followed over the limestone and values obtained were quite uniform, both with respect to the orientation of the line and the electrode separation.

A similar survey conducted over the diabase gave a circular pattern for each electrode separation like that obtained over the limestone, except for some distortion caused by a buried water pipe.

It is concluded that the magnetite deposit was clearly located by the method of induced polarization. This work also indicated that different arrangements of electrodes may serve to improve the measurements and provide still better information on the location of ore bodies.

SUMMARY

A series of laboratory experiments designed to reveal the fundamental relations involved in applying induced polarization to geophysical prospecting has provided a basis for interpreting field data. Advantages and limitations of a prospecting method based on these relations have been established by the experiments and many of the conflicting ideas found in the literature have been resolved.

Any method of geophysical prospecting by induced polarization requires the existence of electrically conducting minerals in an electrolyte. This requirement confines the applicability of the method to the location of electrically conducting minerals and other metallic objects. Oil cannot be directly located by the induced polarization method and it cannot be indirectly located by it unless it is very shallow.

The best application of this method should be to shallow mineral prospecting. It may, however, be used to locate pipe lines, rails, cables and other buried metallic objects. The method does differentiate between those areas where resistivity is low because of metallic conduction and those where it is low because of good electrolytic conduction. The method is also capable of differentiating between two areas of equal resistivity but unequal mineralization. It should be of use therefore in the location of disseminated minerals, such as the galena in the Missouri-Oklahoma-Kansas (Tri-state) region, where the change in resistivity from a mineralized area to an unmineralized one is insufficient to allow detection by resistivity measurements. The ellipse-of-polarization principle increases the usefulness of the method.

The preliminary studies have revealed certain disadvantages in the IP method, several of which are inherent in the method itself and others of which may be eliminated by further development. In the first place, the induced polarization measurement cannot be divorced from the resistivity measurement. This does not mean that separate equipment must be employed or that the resistivity must be separately measured. However, the two separate measurements would undoubtedly be desirable. A more serious limitation upon the method and the one which confines it to shallow work is the "fall-off" of the signal with depth. First, a current density must be established in order to polarize the earth minerals and then the signal must be returned to the surface; this gives, at best, an inverse fourth power relation for the combination. However, the magnitude of the polarization potential increases with the linear dimensions of the body. Another limita-

tion at present is the polarization of disseminated minerals which may mask deeper ore bodies. The effect produced by changes in the concentration of the disseminated mineral is not known. There may be a saturation effect which depends upon the concentration of the mineral particles. Still another limitation, although not serious, lies in the fact that potentials measured by the induced polarization method are usually one order of magnitude lower than those measured by the resistivity method.

It is expected that the method of prospecting by induced polarization will, with improved instrumentation and a larger background of field results, find its place among the existing tools for geophysical prospecting for minerals.

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DEEP-HOLE GEOPHONE STUDY IN GARVIN COUNTY, OKLAHOMA*

R. N. JOLLY†

ABSTRACT

The results of a seismic well survey made with calibrated recording equipment are presented. This survey differed from the conventional type in that a geophone which could be locked to the wall of the bore hole was used, thereby providing reliable amplitude data and permitting reflections to be recorded at depth. Consequently it was possible to observe the true shape and amplitude of the seismic pulses, both initial and reflected, over the major portion of their travel paths. Quantitative data were obtained on such factors as decrease of pulse amplitude with depth, location of reflecting horizons, and magnitude of reflection coefficients.

INTRODUCTION

A great deal of research is being carried out to make the reflection seismograph a better oil finding tool. One obstacle in the way of achieving this objective is our present inadequate understanding of seismic wave propagation in the earth. The problem is so complex for a multi-layered earth that it is virtually unsolvable by mathematical analysis. In the investigation to be discussed in this paper, the direct experimental approach was employed to study the behavior of the seismic pulse as it travels through the earth. By making measurements at a number of depths in a bore hole with a deep hole geophone, it was hoped to attain the following specific objectives: (1) to observe the form of the initial down-traveling pulse and its amplitude decay with depth (or with travel time), (2) to observe reflected pulses and determine depths of reflectors and their reflection coefficients, and (3) to correlate these reflections in time and amplitude with reflections recorded at the surface.

INSTRUMENTS

The instruments used in this survey necessarily involved something of a departure from ordinary seismic equipment. The principal innovation was the use of a deep hole geophone which could be coupled rather rigidly to the wall of the bore hole. The need for such an instrument is illustrated by the frequent difficulties with wind noise, cable kicks, and lack of punch encountered in velocity surveys where a freely hanging geophone is used. A lock-in geophone has these advantages: (1) the amount of powder required is substantially reduced; (2) reliable amplitude measurements may be made, since the geophone is well coupled to the earth; and (3) the noise level is sufficiently small to allow reflections to be recorded because of the fact that the logging cable may be slacked off after the

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geophone is locked in. Reflections are seldom, if ever, recorded with freely hanging geophones because of the high noise level and lack of punch.

A disassembled view of the lock-in deep hole geophone is shown in Figure 1. This instrument was designed by Messrs. A. B. Hildebrandt and R. D. Lynn of the Carter Research Laboratory. The lock-in section consists of three spring-loaded arms of different lengths, which are released by a solenoid located in the tripping mechanism shown on the right. A seismic detector and amplifier are shown on the left. The variable reluctance detector, which has a movement of

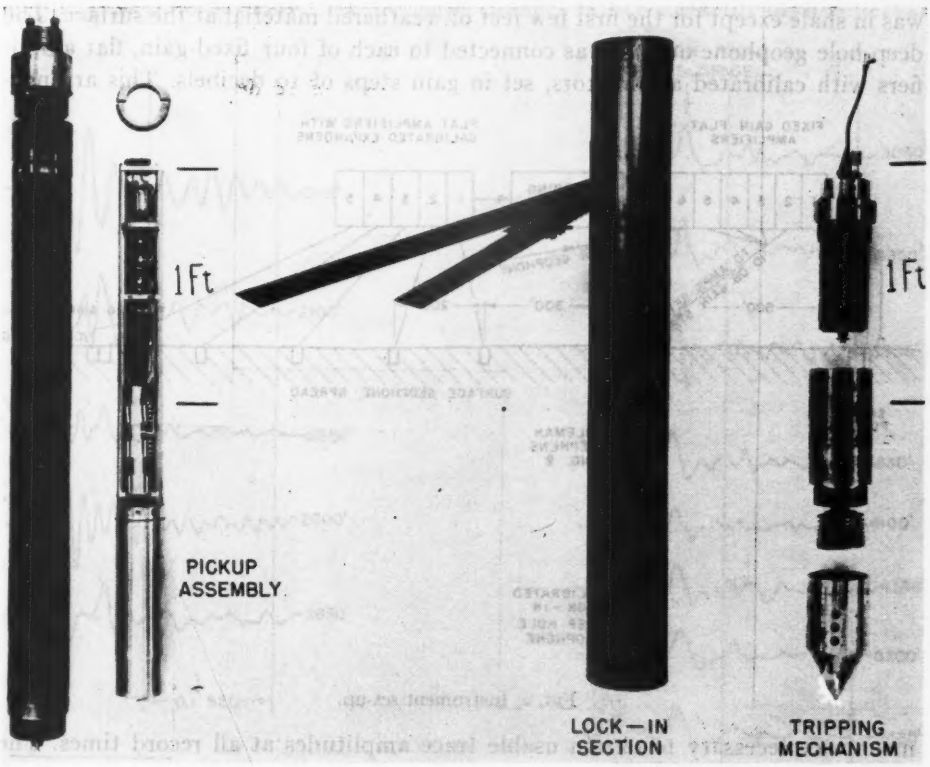


FIG. 1. Disassembled view of lock-in deep hole geophone.

4 c.p.s. natural frequency, is coupled to a pre-amplifier which serves to improve the high frequency response by isolating the detector coil from the distributed capacity of the cable. In addition, it furnishes amplification to improve the signal-to-noise ratio. The geophone is lowered to a position near the bottom of the well, the arms are released by energizing the solenoid from the surface, and the cable is slacked off, allowing the arms to dig in and push the geophone into solid contact with the wall. The geophone is pulled up the hole and the cable is slacked off at each desired depth. Once released, the locking arms cannot be retracted, so that it is necessary for the survey to proceed from the bottom toward the top of the hole.

LOCALE AND PROCEDURE

This work was performed at the Coleman Stephens No. 2 well in the Katie Pool of Garvin County, Oklahoma. This area is in general one of excellent reflection quality, although this particular location was in one of the poorer portions of the area.

Figure 2 shows schematically the instrument set-up used. The shot point was located 500 feet from the well and each charge was 5 pounds at a depth of 60 feet. All records are from charges at the same depth in the same hole, which was in shale except for the first few feet of weathered material at the surface. The deep-hole geophone output was connected to each of four fixed-gain, flat amplifiers with calibrated attenuators, set in gain steps of 10 decibels. This arrange-

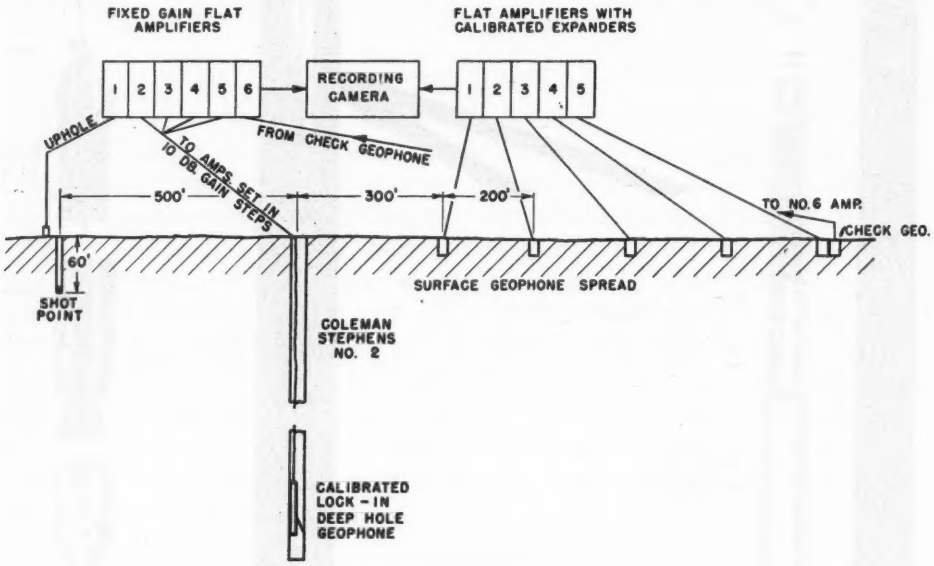


FIG. 2. Instrument set-up.

ment was necessary to obtain usable trace amplitudes at all record times. The other two amplifiers of this set were fed by an uphole geophone and by a check geophone on the surface spread. The check geophone served to monitor the punch provided by each shot. The surface spread of five geophones, located on the opposite side of the well, was connected to the expander type instruments.

The entire recording system, including the geophones and galvanometers, was calibrated absolutely in terms of trace deflection per centimeter per second of geophone case velocity. The calibration method used was that previously described by Ricker (1953, p. 16); it essentially consists of dropping a small steel ball on a suspended geophone and recording the resultant disturbance. By application of the principle of momentum conservation an absolute sensitivity factor for the recording apparatus may be obtained.

RESULTS

From this investigation velocity information was obtained of a type similar to that derived from ordinary velocity surveys. The principal difference was that the time picks of first arrivals, even for the greatest depths, could be made with considerable precision. The traces before first arrivals were almost completely free of noise, and it is believed that the charge size could have been reduced considerably without lowering the accuracy of the time picks.

The behavior of the initial pulse form as it travels downward is shown in Figure 3. It is noteworthy that the shape changes rather markedly in the interval

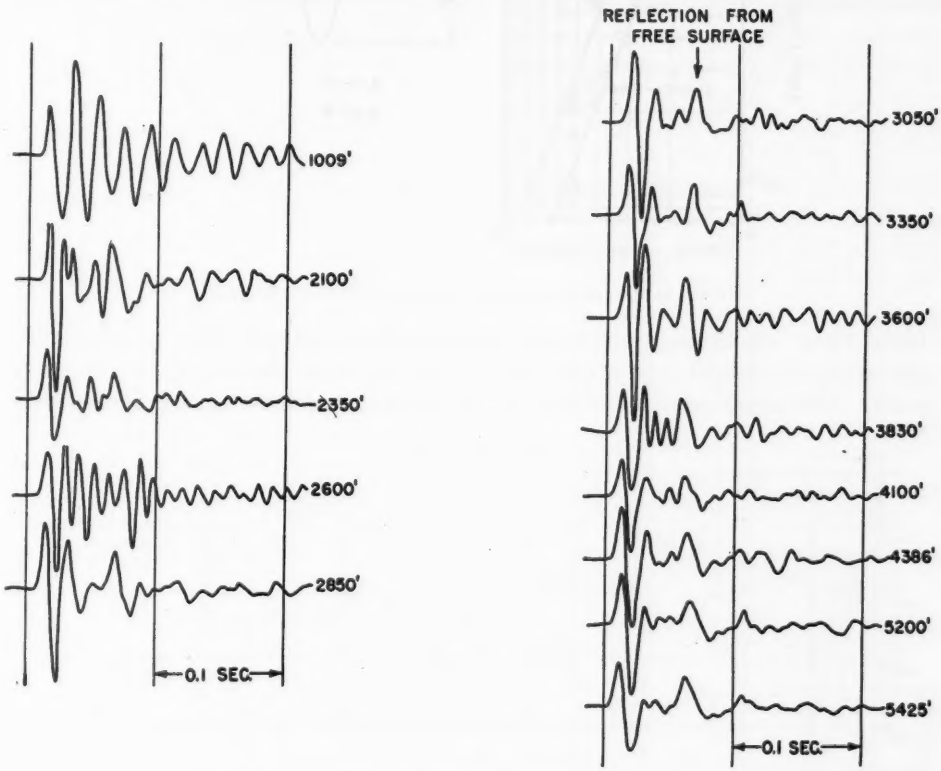


FIG. 3. Initial pulse form as a function of depth.

1,000–3,000 ft. and thereafter changes relatively little. An event labeled as a reflection from the free surface stands out in the lower depth interval. This event, which appears to be an inverted image of the main pulse, lags it by twice the uphole time. Apparently this secondary pulse traveled upward from the shot to the surface where it was reflected downward. It is obvious that the higher frequencies of the initial pulse are attenuated with increasing depth of observation.

Initial pulse amplitude information is presented in Figure 4. Theory (Ricker, 1953, p. 14) suggests that pulse amplitude is proportional to a negative power of

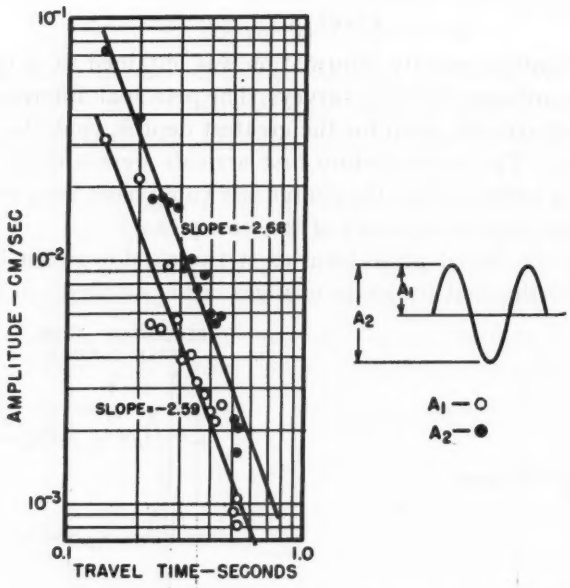


FIG. 4. Initial pulse amplitude as a function of travel time.

travel time. Therefore, if amplitude is plotted against travel time on a logarithmic scale, a straight line should result, and its slope should be this negative power. The amplitudes A_1 and A_2 are so plotted, and least square fits to these

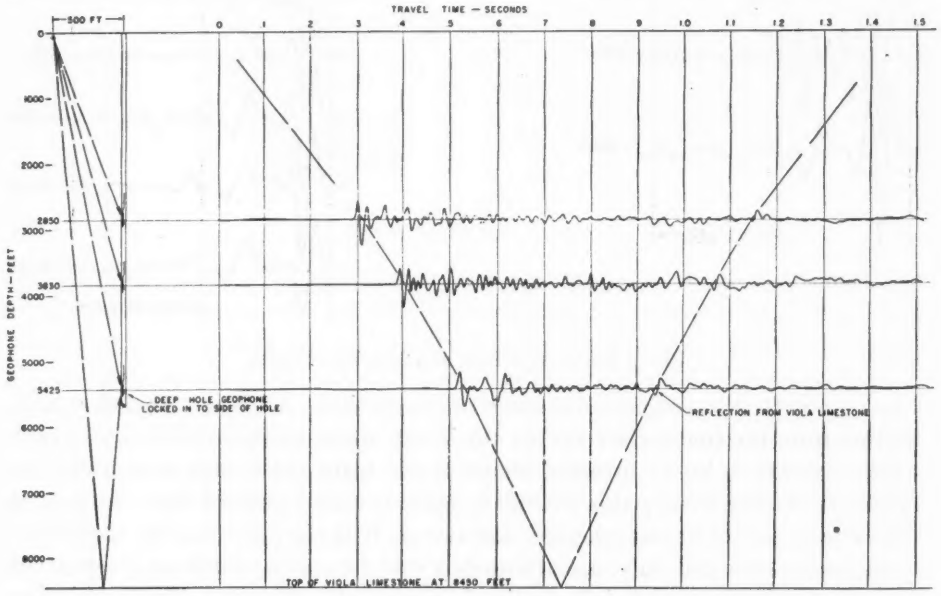


FIG. 5. Showing method of reflection interpretation.

points indicate the initial pulse amplitude to be proportional to the minus 2.6 power of travel time. This compares to an average figure of about 2.4 obtained from previous studies in homogeneous shale sections of eastern Colorado (Ricker, 1953, p. 29).

Figure 5 is used to illustrate the method of picking reflections and determining reflector depths. This is in effect what a three trace record would look like if a vertical profile of three geophones were used with AVC amplifiers. This diagram is derived by tracing three individual records corresponding to three geophone

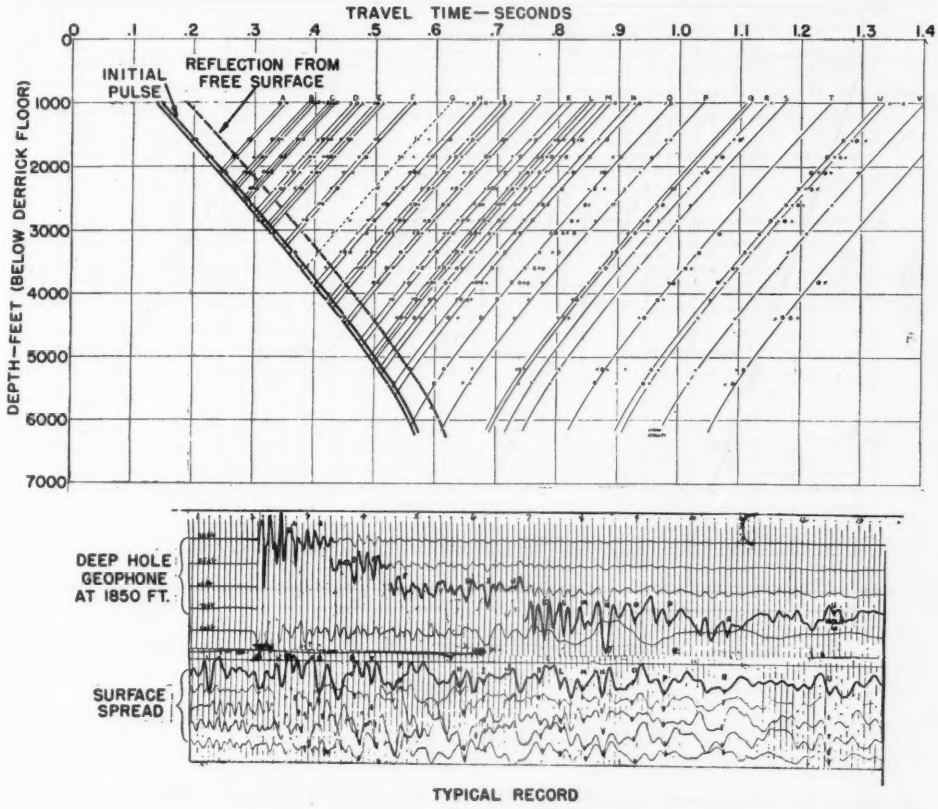


FIG. 6. Depth vs. travel time curves and typical record.

depths. It is seen that the reflection step-out is the negative of the initial pulse step-out, or in effect the reflection time-depth curve has exactly the same shape as the initial pulse curve, but with negative step-out. The character of the Viola reflection shown in the figure is sufficient to identify it as a reflection; however, the character of other events on the record is not sufficiently well maintained to permit their positive identification as such. All events (peaks and valleys) on the individual records which maintained a step-out consistent with the initial pulse step-out were plotted, as shown in Figure 6. It is evident that the intersection of

the extrapolated initial and reflected curves determines the reflector depth, since the geophone must be at the reflector for the initial and reflected travel times to be the same. This method of plotting and interpretation was suggested several years ago by Dr. Norman Ricker of the Carter Research Laboratory.

A time-depth plot of all events which may be reflections is shown in Figure 6. "Negative" or reversed initial pulse curves are passed through these points and it may be noted that most of the points lie on these curves. Thus they may rea-

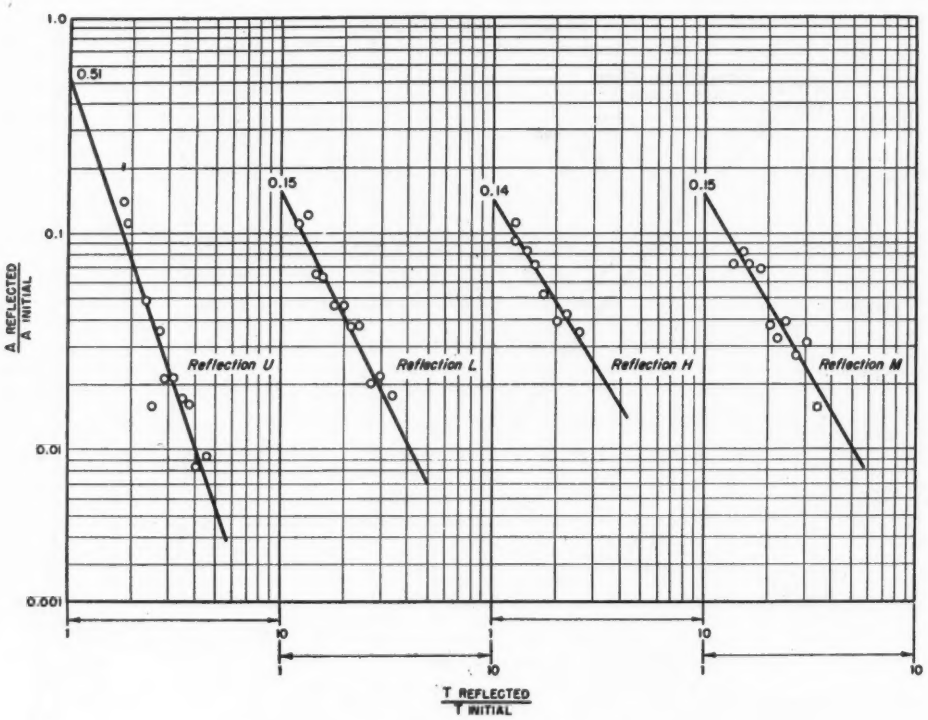
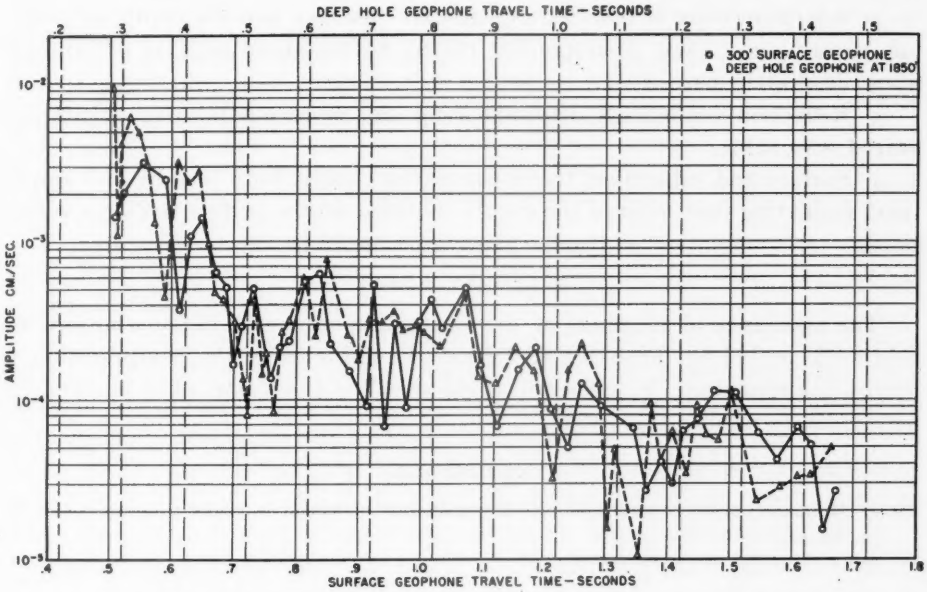


FIG. 7. Determination of reflection coefficients.

sonably be considered reflections. The intersections with the initial pulse curves locate the reflectors. For the most part, the reflectors were found to correspond with lime beds on the electric log. A typical record is shown at the bottom of the figure. Portions of the deep hole geophone traces have been darkened for comparison to a surface spread trace obtained simultaneously. The record has been cut in the middle and the surface traces displaced to the left to account for their longer travel time. It is noted that there is fairly good character correlation between the surface and sub-surface traces, at least for the deeper portions of the record

A determination of the effective reflection coefficients for four of the previously identified reflectors is shown in Figure 7. The ratio of reflected amplitude to initial amplitude is plotted on a logarithmic scale in each case against the ratio of reflected travel time to initial travel time. Each cycle represents a separate graph. When the geophone is very close to the reflector (time ratio very nearly unity) the amplitude ratio should very nearly equal the effective reflection coefficient. In the limit, the extrapolated curve gives the reflection coefficient. These are least squares fits and the reflection coefficients are as shown at the up-


DEEP HOLE GEOPHONE TRAVEL TIME — SECONDS
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10^{-4}
10^{-5}
.4 .5 .6 .7 .8 .9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8
SURFACE GEOPHONE TRAVEL TIME — SECONDS

FIG. 8. Comparison of surface and sub-surface reflection amplitudes.

per end of the line for each reflector. The Viola lime (reflection *U*) has a high reflection coefficient, which accounts for its outstanding appearance on most surface records and the lack of reflections below this depth.

A comparison of surface and subsurface reflection amplitudes is presented in Figure 8. The time scales are displaced to account for the longer travel time to the surface geophone. It is seen that the general trend is remarkably the same, indicating that most of the events recorded at the surface are arriving vertically and are true reflections. This, of course, is a characteristic of a good reflection area. The surface amplitude is in general not less than that at 1,850 feet, as one might expect. However, the surface geophone is at an advantage because of its location at a free surface, which may compensate for the longer travel path.

SUMMARY AND CONCLUSIONS

The behavior of a seismic pulse as it travels through a stratified section in a good seismic area has been reasonably well determined. Specifically, the following facts were ascertained:

1. The amplitude of the initial pulse was found to decay at about the negative 2.6 power of travel time. The initial pulse shape changed appreciably over the first 3,000 feet of travel path and thereafter changed relatively little. It was complicated by the presence of a closely following pulse believed to be a reflection from the free surface.

2. A large number of reflected events were observed and the depths of reflectors determined. These corresponded mostly to limestone beds as determined from the electric log.

3. Reflection coefficients determined for the more outstanding events appeared reasonable.

4. Surface and subsurface traces correlated closely, both in time and amplitude, indicating that most of the events recorded at the surface are true reflections.

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REFERENCE

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THE FIELD OF A MAGNETIC DIPOLE IN THE PRESENCE OF A CONDUCTING SPHERE*

H. W. MARCH†

ABSTRACT

Formulas are derived for the components of the distorted field of a magnetic dipole in the presence of a conducting sphere in a homogeneous medium. In the method employed the field is resolved into two partial fields for the first of which the radial component of the magnetic vector vanishes and for the second of which the radial component of the electric vector vanishes. From the general formulas approximate formulas are derived for the field components in the special case in which the conductivity of the medium is low, the radius of the sphere is not too large and both the dipole and the observer are in the vicinity of the sphere. These approximate formulas are within limits applicable to the problem of locating a spherical body of ore buried in a mass of rock.

INTRODUCTION

A plane coil through which an alternating current is flowing may be regarded as an alternating magnetic dipole at distances from the coil which are great in comparison with its dimensions.

In this paper the general problem is solved of determining the field of such a dipole in the presence of a conducting sphere in a homogeneous medium. From the general formulas approximate expressions are obtained for the field components in the special case in which the conductivity of the medium is low, the radius of the sphere is small and both the dipole and the observer are in the near vicinity of the sphere. These approximate results are, within limits, applicable to the problem of locating a spherical body of ore buried in a mass of rock.

To discuss the field due to a magnetic dipole placed at a point D (Fig. 1) and having an arbitrary orientation with respect to the line OD drawn from O, the center of the sphere, to the dipole it is convenient to study the fields due to two magnetic dipoles, one a "transverse dipole" having its axis perpendicular to the line OD and one a "radial dipole" having its axis along this line. A dipole of any orientation can be resolved into a combination of a transverse and a radial dipole.

THE POTENTIALS Π_1 AND Π_2

The fields will be taken to be periodic with period $2\pi/\omega$. If the electric and magnetic vectors are written in the form[1]

$$\mathcal{E} = \mathcal{R}(Ee^{i\omega t}), \qquad \mathcal{H} = \mathcal{R}(He^{i\omega t}), \tag{1}$$

the field equations, using rational Heaviside electrostatic units, become

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[1] $\mathcal{R}$ denotes "the real part of."

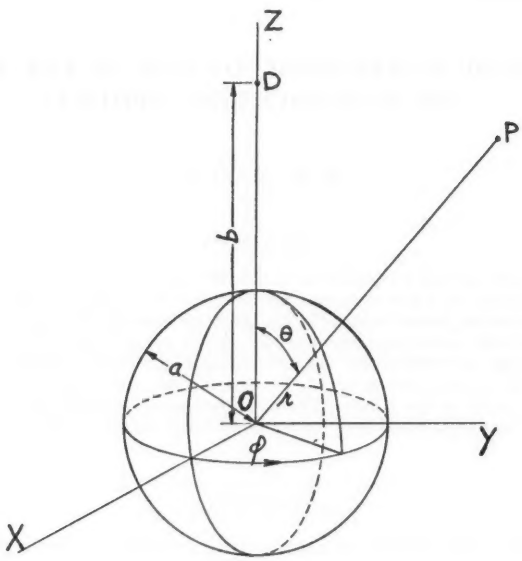

FIG. 1. Conducting sphere and dipole.

$$\begin{aligned} \text{curl } H &= [(i\epsilon\omega + \sigma)/c]E \\ \text{curl } E &= -(i\mu\omega/c)H \end{aligned} \tag{2}$$

where ϵ, μ and σ denote the dielectric constant, the permeability and the conductivity, respectively, of the medium under consideration and c denotes the velocity of light.

Spherical coordinates r, θ, and ϕ will be used with the origin at the center of the sphere as in Fig. 1. The components of the electric vector E in this system of coordinates will be denoted by R, T and F and those of the magnetic vector H by P, Θ and Φ. It will be convenient to use the following notations for combinations of the material constants:

$$\kappa_1 = (i\epsilon\omega + \sigma)/c \tag{3}$$

$$\kappa_2 = i\mu\omega/c \tag{4}$$

$$k^2 = -\kappa_1\kappa_2 = (\epsilon\mu\omega^2 - i\mu\sigma\omega)/c^2. \tag{5}$$

Following Mie (1908) and Debye (1909), consider the field to be resolved into two partial fields for the first of which the radial component of the magnetic vector vanishes and for the second of which the radial component of the electric vector vanishes. Debye (1909) has shown that each field can be derived from a scalar potential. The potentials of the first and second partial fields will be denoted by Π_1 and Π_2 respectively. Subscripts 1 and 2 will denote the components of the corresponding fields.

It is found (Debye, 1909) that the components of the two partial fields are

expressed in terms of the potentials Π_1 and Π_2 by the following equations:

$$R_1 = \frac{\partial^2(r\Pi_1)}{\partial r^2} + k^2 r\Pi_1 \tag{6a}$$

$$T_1 = \frac{1}{r}\frac{\partial^2(r\Pi_1)}{\partial r\partial\theta} \tag{6b}$$

$$F_1 = \frac{1}{r\sin\theta}\frac{\partial^2(r\Pi_1)}{\partial r\partial\phi} \tag{6c}$$

$$P_1 = 0 \tag{7a}$$

$$\Theta_1 = \frac{\kappa_1}{r\sin\theta}\frac{\partial(r\Pi_1)}{\partial\phi} \tag{7b}$$

$$\Phi_1 = -\frac{\kappa_1}{r}\frac{\partial(r\Pi_1)}{\partial\theta}, \tag{7c}$$

$$R_2 = 0 \tag{8a}$$

$$T_2 = -\frac{\kappa_2}{r\sin\theta}\frac{\partial(r\Pi_2)}{\partial\phi} \tag{8b}$$

$$F_2 = \frac{\kappa_2}{r}\frac{\partial(r\Pi_2)}{\partial\theta} \tag{8c}$$

$$P_2 = \frac{\partial^2(r\Pi_2)}{\partial r^2} + k^2 r\Pi_2 \tag{9a}$$

$$\Theta_2 = \frac{1}{r}\frac{\partial^2(r\Pi_2)}{\partial r\partial\theta} \tag{9b}$$

$$\Phi_2 = \frac{1}{r\sin\theta}\frac{\partial^2(r\Pi_2)}{\partial r\partial\phi}. \tag{9c}$$

It is further found that the potentials Π_1 and Π_2 satisfy the differential equation

$$\nabla^2\Pi + k^2\Pi = 0. \tag{10}$$

BOUNDARY CONDITIONS

The solution of each of the problems to be considered consists in finding, corresponding to the primary field of the dipole, the potentials Π_1 and Π_2 of the resulting fields inside and outside the sphere. These potentials are solutions of the differential equation (10) subject to suitable boundary conditions. The boundary conditions follow from the requirement that the tangential components of the

electric and magnetic vectors shall be continuous at the surface of the sphere.

The subscripts or indices i and a will be used to indicate that the quantities to which they are attached are calculated inside or outside the sphere, respectively. The boundary conditions require that

$$T_a = T_i, \qquad F_a = F_i, \qquad \Theta_a = \Theta_i, \qquad \Phi_a = \Phi_i \tag{11}$$

when $r=a$, the radius of the sphere.

If the potentials of the undistorted primary field of the dipole are denoted by Π_1^e and Π_2^e, those of the induced secondary field outside the sphere by Π_1^a and Π_2^a, and those of the total field inside the sphere by Π_1^i and Π_2^i it is readily found on taking account of equations (6), (7), (8) and (9) that the conditions (11) are satisfied if the potentials satisfy the following conditions when $r=a$:

$$\frac{\partial}{\partial r}(r\Pi_j^a + r\Pi_j^e) = \frac{\partial}{\partial r}(r\Pi_j^i) \tag{12}$$

$$\kappa_j^a(r\Pi_j^a + r\Pi_j^e) = \kappa_j^i r\Pi_j^i \tag{13}$$

where j is either 1 in both equations or 2 in both.

PARTICULAR SOLUTIONS

The potentials, Π_1^e and Π_2^e, of the primary field of the given dipole will be expressed in series whose terms are appropriate particular solutions of the differential equation (10). The potentials Π_1^a, Π_2^a, Π_1^i, Π_2^i will be expressed by similar series with coefficients that will be determined so that conditions (12) and (13) are satisfied.

Particular solutions of equation (10) are found in the usual way by letting

$$\Pi = f_1(r)f_2(\theta)f_3(\phi). \tag{14}$$

The functions f_1, f_2, and f_3 are found to satisfy respectively the differential equations:

$$\frac{d^2(rf_1)}{dr^2} + \left[k^2 - \frac{n(n+1)}{r^2}\right]rf_1 = 0 \tag{15}$$

$$\frac{1}{\sin\theta}\frac{d}{d\theta}\left(\sin\theta\,\frac{df_2}{d\theta}\right) + \left[n(n+1) - \frac{\nu^2}{\sin^2\theta}\right]f_2 = 0 \tag{16}$$

$$\frac{d^2f_3}{d\phi^2} + \nu^2 f_3 = 0. \tag{17}$$

The solutions of these differential equations are well known functions. The constants n and ν will be chosen to be integers to secure appropriate particular solutions.

The following solutions of equation (15) will be used:

$$rf_1 = \psi_n(kr) = (\pi kr/2)^{1/2} J_{n+1/2}(kr)$$
$$= \pi^{1/2} \sum_{\gamma=0}^{\infty} (-1)^\gamma \frac{(kr/2)^{2\gamma+n+1}}{\Gamma(\gamma+1)\Gamma(\gamma+n+3/2)}, \tag{18}$$

$$rf_1 = \zeta_n(kr) = (\pi kr/2)^{1/2} H_{n+1/2}^{(2)}(kr)$$
$$= e^{i\pi(n+1)/2} e^{-ikr} \left[1 + \sum_{\gamma=1}^{n} \left(\frac{-i}{2kr}\right)^\gamma \frac{(n-\gamma+1)(n-\gamma+2)\cdots(n+\gamma)}{\gamma!} \right], \tag{19}$$

where $J_{n+1/2}(kr)$ denotes the Bessel's function of the first kind of order $n+1/2$ and $H_{n+1/2}^{(2)}(kr)$ denotes the second Hankel's function of order $n+1/2$. The function $\psi_n(kr)$ vanishes for $r=0$ when $n>-1/2$. The function $\zeta_n(kr)$ becomes infinite at $r=0$ and vanishes for values of its argument having an infinite negative imaginary component. For this reason the constant k for the medium is to be chosen as that root of equation (5) that has a negative imaginary component. Since the factor $e^{i\omega t}$ is to be combined with every solution, it is clear that $\zeta_n(kr)$ is then associated with waves diverging to infinity.

The following recurrence relations are satisfied by the functions $\psi_n(x)$:

$$(2n+1)\psi_n'(x) = (n+1)\psi_{n-1}(x) - n\psi_{n+1}(x)$$
$$(2n+1)\psi_n(x) = x[\psi_{n-1}(x) + \psi_{n+1}(x)]. \tag{20}$$

These relations are also satisfied by the functions $\zeta_n(x)$.

Solutions of equation (16) are the associated functions

$$P_n^\nu(\cos\theta) = \sin^\nu\theta \frac{d^\nu P_n(\cos\theta)}{d(\cos\theta)^\nu} \tag{21}$$

where $P_n(\cos\theta)$ is the surface zonal harmonic of order n.

Solutions of equation (17) are the trigonometric functions, $\sin\nu\phi$ and $\cos\nu\phi$. In what follows it will be found that ν is either 0 or 1. It is to be noted that in accordance with equation (21)

$$P_n^1(\cos\theta) = -\frac{dP_n(\cos\theta)}{d\theta}. \tag{21a}$$

THE TRANSVERSE MAGNETIC DIPOLE

Let a magnetic dipole of unit strength be placed at D, Fig. 1, with its axis perpendicular to OD, the point O being the center of a conducting sphere of radius a. Take OD as the axis of z from which the angle θ is measured and take the axis of x from which the angle ϕ is measured, parallel to the axis of the dipole. Let $OD=b$. The coordinates of any point P are r, θ and ϕ.

By means of the equations[2]

[2] See, for example, Sommerfeld (1927).

$$E_e = -\kappa_2{}^a \operatorname{curl} Z_0 \tag{22}$$

$$H_e = \operatorname{grad} \operatorname{div} Z_0 + k_a{}^2 Z_0, \tag{23}$$

the electric and magnetic vectors E_e and H_e of the primary field due to the unit dipole can be derived from the Hertz vector function

$$Z_0 = Me^{-ik_a\rho}/\rho \tag{24}$$

where

$$\rho = (b^2 + r^2 - 2br\cos\theta)^{1/2} \tag{25}$$

and M is a unit vector having the direction of the axis of the dipole.

The function $e^{-ik_a\rho}/\rho$ admits (Nielsen, 1904) the following expansion:

$$e^{-ik_a\rho}/\rho = \sum_{n=0}^{\infty} c_n[\zeta_n(k_a r)/r]P_n(\cos\theta), \quad \text{if} \quad r > b \tag{26}$$

$$e^{-ik_a\rho}/\rho = \sum_{n=0}^{\infty} d_n[\psi_n(k_a r)/r]P_n(\cos\theta), \quad \text{if} \quad r < b \tag{27}$$

where

$$c_n = -i(2n+1)\psi_n(k_a b)/k_a b \tag{28}$$

$$d_n = -i(2n+1)\zeta_n(k_a b)/k_a b. \tag{29}$$

The r, θ, and ϕ components of the vector Z_0 that are needed in the calculation of the components of the primary field are obtained by multiplying $e^{-ik_a\rho}/\rho$ by $\cos\phi\sin\theta$, $\cos\phi\cos\theta$, and $(-\sin\phi)$, respectively. By using the series (27) and equation (22) the components R_e and T_e of the primary electric vector E_e in the region $r<b$ are found to be:

$$R_e = -\kappa_2{}^a \sin\phi \sum_{n=1}^{\infty} d_n(\psi_n/r^2)P_n{}^1 \tag{30}$$

$$T_e = -\kappa_2{}^a \sin\phi \sum_{n=0}^{\infty} d_n[(\psi_n/r^2) - k_a\psi_n'/r]P_n. \tag{31}$$

For convenience in writing, the arguments $k_a r$ and $\cos\theta$ of ψ_n and P_n, respectively, are omitted for the present. The expressions for the components R_e and T_e of the primary field will be used to find the potentials $\Pi_1{}^e$ and $\Pi_2{}^e$ of the partial fields into which this field can be resolved. The components of the two partial primary fields will be denoted by R_{1e}, T_{1e}, etc. and R_{2e}, T_{2e}, etc. Then

$$R_e = R_{1e} + R_{2e}, \qquad T_e = T_{1e} + T_{2e}. \tag{32}$$

Now $R_{2e}=0$ in accordance with equation (8a). Hence

$$R_{1e} = R_e. \tag{33}$$

Accordingly R_{1e} is expressed by equation (30). The component R_{1e} is also expressed in terms of the potential Π_1^e by equation (6*a*). The potential Π_1^e may be represented by the following series, with undetermined coefficients a_n, of particular solutions of the differential equation (10):

$$\Pi_1^e = \sin\phi \sum_{n=1}^{\infty} a_n(\psi_n/r)P_n^1. \tag{34}$$

By calculating R_{1e} from this equation by means of equation (6*a*) and comparing the coefficients of the resulting expression with those of equation (30) it is found that

$$a_n = -\kappa_2{}^a d_n/n(n+1). \tag{35}$$

Hence

$$\Pi_1^e = -\kappa_2{}^a \sin\phi \sum_{n=1}^{\infty} [d_n/n(n+1)](\psi_n/r)P_n^1. \tag{36}$$

The potential Π_2^e will be obtained by considering a component T_{2e} of the second partial primary field. Now

$$T_{2e} = T_e - T_{1e}. \tag{37}$$

By using equation (6*b*) the component T_{1e} is obtained from Π_1^e (equation (36)) and is found to be

$$T_{1e} = -\kappa_2{}^a \sin\phi \sum_{n=1}^{\infty} \frac{k_a d_n \psi_n'}{n(n+1)r} \frac{dP_n^1}{d\theta}. \tag{38}$$

On subtracting this expression from that for T_e (equation (31)) it follows that

$$T_{2e} = \kappa_2{}^a \sin\phi \left\{ d_0 \left(\frac{\psi_0}{r^2} - \frac{k_a \psi_0'}{r} \right) + \sum_{n=1}^{\infty} d_n \left[\left(\frac{\psi_n}{r^2} - \frac{k_a \psi_n'}{r} \right) P_n + \frac{k_a \psi_n'}{n(n+1)r} \frac{dP_n^1}{d\theta} \right] \right\}. \tag{39}$$

In accordance with equation (8*b*),

$$T_{2e} = -\frac{\kappa_2{}^a}{r \sin\theta} \frac{\partial r \Pi_2{}^e}{\partial \phi}. \tag{40}$$

It follows from equations (39) and (40) that

$$\Pi_2{}^e = \cos\phi \left\{ d_0 \left(\frac{\psi_0}{r^2} - \frac{k_a \psi_0'}{r} \right) \sin\theta + \sum_{n=1}^{\infty} d_n \sin\theta \left[\frac{\psi_n}{r^2} P_n + \frac{k_a \psi_n'}{n(n+1)r} \left(\frac{dP_n^1}{d\theta} - n(n+1)P_n \right) \right] \right\}. \tag{41}$$

A function of r and θ is not added because from the orientation of the dipole, terms independent of ϕ are not to be expected. This can be confirmed by calculating $P_{2e}=P_e$ by using equation (23) and noting equation (9a).

An extensive simplification of equation (41) can be made by using successively: (a) the differential equation satisfied by P_n; (b) recurrence formulas for P_n; (c) the definition of d_n from equation (29) followed by a regrouping of terms; (d) the first of relations (20), a relation satisfied by $\zeta_n(k_a b)$. It is finally found that

$$\Pi_2^e = -(i\cos\phi/b)\sum_{n=1}^{\infty}[(2n+1)/n(n+1)]\zeta_n'(k_a b)[\psi_n(k_a r)/r]P_n^1(\cos\theta). \quad (42)$$

The potentials Π_1^e and Π_2^e (equations (36) and (42)) will now be written in the forms:

$$\Pi_1^e = \sin\phi\sum_{n=1}^{\infty}\alpha_n[\psi_n(k_a r)/r]P_n^1(\cos\theta) \quad (43)$$

$$\Pi_2^e = \cos\phi\sum_{n=1}^{\infty}\beta_n[\psi_n(k_a r)/r]P_n^1(\cos\theta) \quad (44)$$

where

$$\alpha_n = i\kappa_2{}^a(2n+1)\zeta_n(k_a b)/n(n+1)k_a b \quad (45)$$

$$\beta_n = -i(2n+1)\zeta_n'(k_a b)/n(n+1)b. \quad (46)$$

Let the potentials of the secondary fields outside the sphere and of the total fields inside the sphere be represented by the series:

$$\Pi_1^a = \sin\phi\sum_{n=1}^{\infty}a_{1n}[\zeta_n(k_a r)/r]P_n^1(\cos\theta) \quad (47)$$

$$\Pi_1^i = \sin\phi\sum_{n=1}^{\infty}b_{1n}[\psi_n(k_i r)/r]P_n^1(\cos\theta) \quad (48)$$

$$\Pi_2^a = \cos\phi\sum_{n=1}^{\infty}a_{2n}[\zeta_n(k_a r)/r]P_n^1(\cos\theta) \quad (49)$$

$$\Pi_2^i = \cos\phi\sum_{n=1}^{\infty}b_{2n}[\psi_n(k_i r)/r]P_n^1(\cos\theta). \quad (50)$$

The constant k_i that appears in the equations applying to the sphere will for the sake of definiteness be chosen as that root of equation (5) that has a negative imaginary component. The other root might equally well have been chosen.

From the boundary conditions (12) and (13) it is found that

$$a_{1n} = -\frac{k_i\kappa_1{}^a\psi_n(k_a a)\psi_n'(k_i a) - k_a\kappa_1{}^i\psi_n'(k_a a)\psi_n(k_i a)}{k_i\kappa_1{}^a\zeta_n(k_a a)\psi_n'(k_i a) - k_a\kappa_1{}^i\zeta_n'(k_a a)\psi_n(k_i a)}\alpha_n. \quad (51)$$

The expression for the coefficient b_{1n}, associated with the field in the interior of the sphere, is obtained in like manner but it will not be written down. If problems requiring this coefficient are considered it should be noted that a considerable simplification can be effected by using the known relation:

$$\zeta_n(k_a a)\psi_n'(k_a a) - \zeta_n'(k_a a)\psi_n(k_a a) = \text{const.} = i. \tag{52}$$

The coefficients a_{2n} and b_{2n} are obtained from the expressions for a_{1n} and b_{1n} by replacing κ_1 by κ_2 and α_n by β_n.

Equations (43), (44), and (47)–(50) give the potentials from which the fields can be calculated in the regions inside and outside the sphere. In a later section approximate expressions for the components of the secondary field outside the sphere will be obtained for the case where the radius of the sphere is small. It will be simpler to calculate the primary field directly without making use of the two potentials.

THE RADIAL MAGNETIC DIPOLE

Let the dipole be placed at D (Fig. 1) at a distance b from the center of the sphere, and let its axis lie along the line OD. The primary field is derived from the Hertz vector function

$$Z_0 = Me^{-ik_a\rho}/\rho \tag{53}$$

where M is a unit vector parallel to OD and ρ is defined by equation (25).

The r and θ-components of the vector Z_0 that are needed in the calculation of the primary field are obtained by multiplying $e^{-ik_a\rho}/\rho$ by $\cos\theta$ and $(-\sin\theta)$, respectively. The ϕ-component vanishes.

The symmetry of the field about the axis OD suggests the following choice for the potentials Π_1^e and Π_2^e:

$$\Pi_1^e = 0, \qquad \Pi_2^e = Ce^{-ik_a\rho}/\rho. \tag{54}$$

It can be shown that all of the components of the primary field as found from the vector Z_0 by using equations (22) and (23) are correctly obtained from this choice of the potentials if C in equation (54) is chosen equal to $1/b$. Then in accordance with equation (27),

$$\Pi_2^e = (1/b)\sum_{n=0}^{\infty} d_n[\psi_n(k_a r)/r]P_n(\cos\theta) \tag{55}$$

where d_n is defined by equation (29).

To find the secondary field outside the sphere and the total field inside the sphere, let

$$\Pi_2^a = (1/b)\sum_{n=0}^{\infty} e_n[\zeta_n(k_a r)/r]P_n(\cos\theta) \tag{56}$$

$$\Pi_2{}^i = (1/b)\sum_{n=0}^{\infty} f_n[\psi_n(k_i r)/r]P_n(\cos\theta) \tag{57}$$

and determine e_n and f_n from the boundary conditions (12) and (13). It is found that

$$e_n = -\frac{k_i\kappa_2{}^a\psi_n(k_a a)\psi_n'(k_i a) - k_a\kappa_2{}^i\psi_n'(k_a a)\psi_n(k_i a)}{k_i\kappa_2{}^a\zeta_n(k_a a)\psi_n'(k_i a) - k_a\kappa_2{}^i\zeta_n'(k_a a)\psi_n(k_i a)}\, d_n. \tag{58}$$

The coefficient f_n, which can be readily obtained, is not written down as it is associated with the field in the interior of the sphere.

APPROXIMATE EXTERNAL SECONDARY FIELD. RADIUS OF THE SPHERE SMALL

From the formulas that have been derived, approximate formulas for the secondary field will be obtained for the case of a dipole in the vicinity of a sphere of sufficiently small radius and high conductivity surrounded by a medium of low conductivity.

The conductivity, dielectric constant and magnetic permeability of the sphere will be denoted by σ_i, ϵ_i and μ_i, respectively, and the corresponding constants of the medium by σ_a, ϵ_a and μ_a. It will be assumed that $\mu_i = \mu_a = 1$.

For a sphere of high conductivity such that $\epsilon_i\omega/\sigma_i \ll 1$ it follows from equations (3) and (5) that

$$k_i = e^{-i\pi/4}(\sigma_i\omega)^{1/2}/c, \qquad \kappa_1{}^i = \sigma_i/c \tag{59}$$

approximately.

In obtaining approximate expressions for the terms of the series representing the field components, the sphere will at first be considered to be a perfect conductor. It will be pointed out that for a considerable range of the quantities involved, the formulas that hold for the perfectly conducting sphere may be expected to be adequate in the case of a sphere of finite but high conductivity.

The radius of the sphere will be assumed to be sufficiently small, so that $|k_a a| \ll 1$ where

$$k_a{}^2 = (\epsilon_a\omega^2 - i\sigma_a\omega)/c^2.$$

It will further be assumed that the dipole and the observer are so near to the sphere that the following inequalities hold:

$$|k_a r| \ll 1, \qquad |k_a b| \ll 1.$$

(a) *Transverse Dipole*

In the case of the transverse magnetic dipole the potential $\Pi_1{}^a$ of the first partial secondary field (equations (47) and (51)) can be written in the form

$$\Pi_1{}^a = -i(\kappa_2{}^a \sin\phi/k_a b r)\sum_{n=1}^{\infty}[(2n+1)/n(n+1)]C_n[\psi_n(k_a a)/\zeta_n(k_a a)] \cdot \zeta_n(k_a b)\zeta_n(k_a r)P_n{}^1(\cos\theta) \tag{60}$$

where

$$C_n = \frac{(k_i\kappa_1{}^a/k_a\kappa_1{}^i)\left[\psi_n'(k_ia)/\psi_n(k_ia)\right] - \left[\psi_n'(k_aa)/\psi_n(k_aa)\right]}{(k_i\kappa_1{}^a/k_a\kappa_1{}^i)\left[\psi_n'(k_ia)/\psi_n(k_ia)\right] - \left[\zeta_n'(k_aa)/\zeta_n(k_aa)\right]}. \tag{61}$$

It is readily found that

$$\lim_{\sigma_i\to\infty}(k_i\kappa_1{}^a/k_a\kappa_1{}^i) = \lim_{\sigma_i\to\infty}\left[(i\epsilon_a\omega^2+\sigma_a)/(i\epsilon_i\omega^2+\sigma_i)\right]^{1/2} = 0.$$

By using the asymptotic formula[3] for $J(x)_{n+1/2}$ for an argument large in absolute value it can be shown by noting equation (59) that

$$\lim_{\sigma_i\to\infty}\left[\psi_n'(k_ia)/\psi_n(k_ia)\right] = i. \tag{62}$$

Hence the first term in the numerator and denominator of the expression for C_n vanishes in the case of a perfectly conducting sphere. If the conductivity of the sphere is finite but high this term will be small in comparison with the second terms whose approximate values are found in the next paragraph.

For small absolute values of the argument x the following approximate formulas are obtained from equations (18) and (19) by neglecting terms containing x^2 and higher powers of x:

$$\begin{aligned}
\psi_n(x) &\cong x^{n+1}/1\cdot 3\cdots(2n+1)\\
\psi_n'(x) &\cong (n+1)x^n/1\cdot 3\cdots(2n+1)\\
\zeta_n(x) &\cong i(2n)!/x^n 2^n n!\\
\zeta_n'(x) &\cong -i(2n)!/x^{n+1}2^n(n-1)!.
\end{aligned} \tag{63}$$

Hence the second terms in the numerator and denominator of the expression for C_n have the approximate values $(n+1)/k_aa$ and $-n/k_aa$ respectively. It is with these values that the first term in the numerator and denominator has to be compared in the case of a sphere of finite conductivity.

After omitting the first term in the numerator and denominator of the expression (61) for C_n, equation (60) becomes

$$\Pi_1{}^a = -i(\kappa_2{}^a\sin\phi/k_abr)\sum_{n=1}^{\infty}\left[(2n+1)/n(n+1)\right] \cdot\left[\psi_n'(k_aa)/\zeta_n'(k_aa)\right]\zeta_n(k_ab)\zeta_n(k_ar)P_n{}^1(\cos\theta). \tag{64}$$

By using formulas (63) and the values of the associated functions $P_n{}^1(\cos\theta)$ in terms of the trigonometric functions the following approximate series for $\Pi_1{}^a$ is obtained:

$$\Pi_1{}^a = -\kappa_2{}^a\sin\phi\sin\theta(a^3/b^2r^2)\left[1+(3a^2/4br)\cos\theta + (a^4/6b^2r^2)(5\cos^2\theta-1)+\cdots\right]. \tag{65}$$

[3] The formula is exact for the index $n+\frac{1}{2}$ when n is an integer.

Since a is less than both b and r the series in equation (65) converges rapidly in most cases of interest.

The components of the first partial secondary field are to be calculated by equations (6) and (7). For the cases under consideration it can be shown that the approximate expression (65) for Π_1^a may be used instead of first using the exact expression and then making the approximations in the formulas for each of the components. It is to be noted that, in calculating the component R_1^a from (65), the terms arising from $k_a^2\Pi_1^a$ are negligible in accordance with the assumption that $|k_a r| \ll 1$. The approximate components of the first partial secondary field of the transverse magnetic dipole are thus found to be:

$$R_1^a = -\kappa_2^a \sin\phi \sin\theta(2a^3/b^2r^3)\left[1 + (9a^2/4br)\cos\theta + (a^4/b^2r^2)(5\cos^2\theta - 1) + \cdots\right] \tag{66}$$

$$T_1^a = \kappa_2^a \sin\phi(a^3/b^2r^3)\left[\cos\theta + (3a^2/2br)\cos 2\theta + (a^4/2b^2r^2)(15\cos^2\theta - 11)\cos\theta + \cdots\right] \tag{67}$$

$$F_1^a = \kappa_2^a \cos\phi(a^3/b^2r^3)\left[1 + (3a^2/2br)\cos\theta + (a^4/2b^2r^2)(5\cos^2\theta - 1) + \cdots\right] \tag{68}$$

$$P_1^a = 0 \tag{69}$$

$$\Theta_1^a = k_a^2 \cos\phi(a^3/b^2r^2)\left[1 + (3a^2/4br)\cos\theta + (a^4/6b^2r^2)(5\cos^2\theta - 1) + \cdots\right] \tag{70}$$

$$\Phi_1^a = -k_a^2 \sin\phi(a^3/b^2r^2)\left[\cos\theta + (3a^2/4br)\cos 2\theta + (a^4/6b^2r^2)(15\cos^2\theta - 11)\cos\theta + \cdots\right]. \tag{71}$$

In accordance with equation (49) in which the expression for the coefficient a_{2n} is to be obtained from that for a_{1n} (equation (51)) by replacing κ_1 by κ_2 and α_n by β_n (equation (46)), the potential Π_2^a of the second partial secondary field outside the sphere can be written in the following form:

$$\Pi_2^a = (i\cos\phi/br)\sum_{n=1}^{\infty}\left[(2n+1)/n(n+1)\right]D_n\left[\psi_n(k_a a)/\zeta_n(k_a a)\right] \cdot \zeta_n'(k_a b)\zeta_n(k_a r)P_n^1(\cos\theta) \tag{72}$$

where

$$D_n = \frac{1 - \left[\psi_n'(k_a a)/\psi_n(k_a a)\right]\left[\psi_n(k_i a)/\psi_n'(k_i a)\right](k_a/k_i)}{1 - \left[\zeta_n'(k_a a)/\zeta_n(k_a a)\right]\left[\psi_n(k_i a)/\psi_n'(k_i a)\right](k_a/k_i)}. \tag{73}$$

If as before it is assumed that $k_a a$ is small in absolute value it is readily shown that

$$\lim_{\sigma_i \to \infty} D_n = 1. \tag{74}$$

Hence for a perfectly conducting sphere the coefficients D_n in equation (72) may be replaced by unity. By doing so an adequate approximation will also be obtained for a sphere of finite but high conductivity.

On replacing the coefficients D_n by unity and using the formulas (63) for the functions of the small arguments $k_a a$, $k_a b$, and $k_a r$ it is found from equation (72) that

$$\Pi_2{}^a = \cos\phi \sin\theta (a^3/2b^3r^2)\left[1 + (2a^2/br)\cos\theta + (3a^4/4b^2r^2)(5\cos^2\theta - 1) + \cdots\right]. \quad (75)$$

The components of the second partial secondary field are to be calculated by equations (8) and (9) from the approximate expression (75) for $\Pi_2{}^a$. In the case of the component $P_2{}^a$ it is to be noted that the terms arising from $k_a{}^2\Pi_2{}^a$ are negligible in accordance with the assumption that $|k_a r| \ll 1$. The approximate components of the second partial secondary field are found to be:

$$R_2{}^a = 0 \quad (76)$$

$$T_2{}^a = \kappa_2{}^a \sin\phi (a^3/2b^3r^2)\left[1 + (2a^2/br)\cos\theta + (3a^4/4b^2r^2)(5\cos^2\theta - 1) + \cdots\right] \quad (77)$$

$$F_2{}^a = \kappa_2{}^a \cos\phi (a^3/2b^3r^2)\left[\cos\theta + (2a^2/br)\cos 2\theta + (3a^4/4b^2r^2)(15\cos^2\theta - 11)\cos\theta + \cdots\right] \quad (78)$$

$$P_2{}^a = \cos\phi \sin\theta (a^3/b^3r^3)\left[1 + (6a^2/br)\cos\theta + (9a^4/2b^2r^2)(5\cos^2\theta - 1) + \cdots\right] \quad (79)$$

$$\Theta_2{}^a = -\cos\phi (a^3/2b^3r^3)\left[\cos\theta + (4a^2/br)\cos 2\theta + (9a^4/4b^2r^2)(15\cos^2\theta - 11)\cos\theta + \cdots\right] \quad (80)$$

$$\Phi_2{}^a = \sin\phi (a^3/2b^3r^3)\left[1 + (4a^2/br)\cos\theta + (9a^2/4b^2r^2)(5\cos^2\theta - 1) + \cdots\right]. \quad (81)$$

The components of the total secondary field outside the sphere are obtained by combining the components of the two partial fields as given by equations (66) to (71) and (76) to (81). It is to be noted that since $k_a a$, $k_a b$, and $k_a r$ have all been assumed to be small, the components $\Theta_1{}^a$ and $\Phi_1{}^a$ can be neglected in comparison with $\Theta_2{}^a$ and $\Phi_2{}^a$, respectively.

(b) *Radial Dipole*

The components of the secondary field are obtained entirely from the potential $\Pi_2{}^a$ since the potential $\Pi_1{}^a = 0$. From equations (56) and (58) it follows that

$$\Pi_2{}^a = (i/k_a b^2 r)\sum_{n=0}^{\infty}(2n+1)D_n\left[\psi_n(k_a a)/\zeta_n(k_a a)\right]\zeta_n(k_a b)\zeta_n(k_a r)P_n(\cos\theta) \quad (82)$$

where D_n is defined by equation (73). It has been seen that for a perfectly con-

ducting sphere the coefficients D_n can be replaced by unity.

On using the approximate formulas (63) for the functions ψ_n and ζ_n with small arguments and equations (8) and (9), the approximate expressions for the field components are found to be

$$R_2{}^a = 0 \tag{83}$$

$$T_2{}^a = 0 \tag{84}$$

$$F_2{}^a = \kappa_2{}^a(a^3 \sin\theta/b^3r^2)\left[1 + (3a^2/br)\cos\theta + (3a^4/2b^2r^2)(5\cos^2\theta - 1) + \cdots\right] \tag{85}$$

$$P_2{}^a = -(2a^3/b^3r^3)\left[\cos\theta + (3a^2/2br)(3\cos^2\theta - 1) + (3a^4/b^2r^2)(5\cos^2\theta - 3)\cos\theta + \cdots\right]. \tag{86}$$

$$\Theta_2{}^a = -(a^3 \sin\theta/b^3r^3)\left[1 + (6a^2/br)\cos\theta + (9a^4/2b^2r^2)(5\cos^2\theta - 1) + \cdots\right] \tag{87}$$

$$\Phi_2{}^a = 0. \tag{88}$$

CONCLUSION

In the preceding section approximate formulas have been derived for the components of the secondary field induced by a conducting sphere in the presence of a transverse and a radial magnetic dipole, each of unit strength, when the radius of the sphere is small and the dipole and observer are sufficiently near to the sphere. From these results the components of the secondary field associated with a dipole of any orientation and strength are readily obtained. The components of the primary field can be calculated directly from the Hertz vector function for each type of dipole. The combination of the primary and secondary fields gives the actual field. It is to be recalled that the factor $e^{i\omega t}$which has been suppressed throughout must be taken into account in accordance with equations (1).

If the assumptions under which the approximate formulas of the preceding section were derived are not satisfied, recourse must be had to the exact formulas (47), (49), and (56) for the potentials of the secondary field and suitable methods of calculation must be developed for the case under consideration.

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RADIATION FROM A CYLINDRICAL SOURCE OF FINITE LENGTH*

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ABSTRACT

This paper presents the results of a theoretical study of radiation from a cylindrical source of finite length, the walls of which are subjected to symmetric lateral and tangential stresses. Three divergent wave systems are generated, P, SV, and SH, and their amplitudes are calculated in terms of the stresses operative on the walls of the "equivalent cavity." The zonal distribution of amplitude in the three wave systems is calculated, and the total amount of energy in each is estimated. It is shown that under the action of a lateral pressure only, an SV wave of amplitude 1.6 times the maximum amplitude of the associated P-wave is beamed from the source in directions making angles of 45° with the axis of the source.

This paper is the first of a series embodying the results of a study of the nature and origin of elastic head waves.[1] It was thought well to begin this study by attempting to reproduce in mathematical form the main features of the type of disturbance most frequently employed in seismic prospecting, namely, that generated by the detonation of a charge in a cylindrical shot hole. The problem we were led to consider was the effect of transitory forces acting upon the walls of a cylindrical cavity of finite length embedded in an infinite solid medium. The results of this part of the enquiry are presented in this paper.

When energy is imparted to the ground by an explosion, some is converted into a radiating stress-strain field and some is utilized in producing local deformations of a permanent character. The precise mechanism by which energy is transmitted to the ground is not clear. Considerable research has been done on this type of problem by United States Army and Navy engineers, but the results of the research are not yet available to the public. The energy carrier, however, seems to be a shock wave which travels through the medium with supersonic speed, exepending its energy in breaking and crushing the surrounding rock, and gradually diminishing in intensity through diffusion over an ever broadening wave front. When the stresses in the expanding wave no longer exceed the strength of the medium, the shock wave has become an elastic wave and from there on is propagated according to the well-known laws of elastic wave theory. How the total energy imparted to the medium by a purely elastic disturbance is partitioned between a field of permanent deformation and a radiating field of force has been investigated for certain simple sources by Kawasumi and Yoshiyama, Sezawa, and Kanai. Sezawa[2] concluded that not more than half of the

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[1] This study was part of a doctoral program undertaken by the author under the direction of the Reverend James B. Macelwane, S.J., at Saint Louis University in 1952.

[2] K. Sezawa, "Elastic Waves Produced by Applying a Statical Force to a Body or by Releasing It from a Body," *Bull. Earth. Res. Inst., Tokyo*, 13, (1935), 740–748; "On the Relation between Seismic Origins and Radiated Waves," *ibid.*, 14, (1936), 149–154; K. Sezawa and K. Kanai, "Elastic Waves Formed by Local Stress Changes of Different Rapidities," *ibid.*, 10–17.

total energy is ever present in the radiating field, and this much only when the disturbing force is applied or released with great rapidity.

Theoretical studies of the radiation from different types of sources have been made by Sezawa, Kanai, Nishimura and Takayama.[3] In this paper, with a view to simulating conditions in the neighborhood of a shot hole, the source chosen is a cylinder of length $2l$ and radius a, centered at the origin of co-ordinates and embedded in an infinite medium. The vertical walls of this cylinder are subjected to stresses which are symmetric about the vertical axis, uniform in the sense that they have the same instantaneous value at all points, and finite in duration.

Expressing the conditions mathematically in cylindrical co-ordinates (r, θ, z), the conditions at the source become (see Fig. 1):

$$[-\widehat{rr}] = p(t) \quad \text{or o, according as } |z| < l \text{ or } > l, \tag{1a}$$

$$[-\widehat{rz}] = q(t) \quad \text{or o, according as } |z| < l \text{ or } > l, \tag{1b}$$

$$[-\widehat{r\theta}] = s(t) \quad \text{or o, according as } |z| < l \text{ or } > l. \tag{1c}$$

It can be assumed that $p(t)$, $q(t)$ and $s(t)$ are proportional to one another.

Since the deformation is, by hypothesis, symmetrical about the z-axis at all times, the displacement (u, v, w) can be expressed in terms of three wave-functions Φ_0, Θ_0, and χ_0 which satisfy the following wave equations,

$$\begin{aligned} \Phi_0'' - V^2\nabla^2\Phi_0 &= 0, \\ \Theta_0'' - v^2\nabla^2\Theta_0 &= 0, \\ \chi_0'' - v^2\nabla^2\chi_0 &= 0, \end{aligned} \tag{2}$$

where $V = (\lambda+2\mu)^{1/2}/\rho^{1/2}$, $v = \mu^{1/2}/\rho^{1/2}$. The quantities (u, v, w)[4] are the components of particle displacement in the directions of (r, θ, z) increasing respectively. These displacements, when expressed in terms of the auxiliary wave functions, are

$$u = \frac{\partial\Phi_0}{\partial r} - \frac{\partial^2\Theta_0}{\partial r\partial z}, \tag{3a}$$

$$v = \frac{\partial\chi_0}{\partial r}, \tag{3b}$$

$$w = \frac{\partial\Phi_0}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\Theta_0}{\partial r}\right). \tag{3c}$$

The stresses, likewise expressed in terms of the auxiliary functions, take the form,

[3] Cf. *Bull. Earth. Res. Inst., Tokyo,* volumes 2 (1927), 14 (1936) and 16 (1938).

[4] The author employs the symbol v both for tangential displacement and shear velocity. The context will make clear which meaning is intended—The Editor.

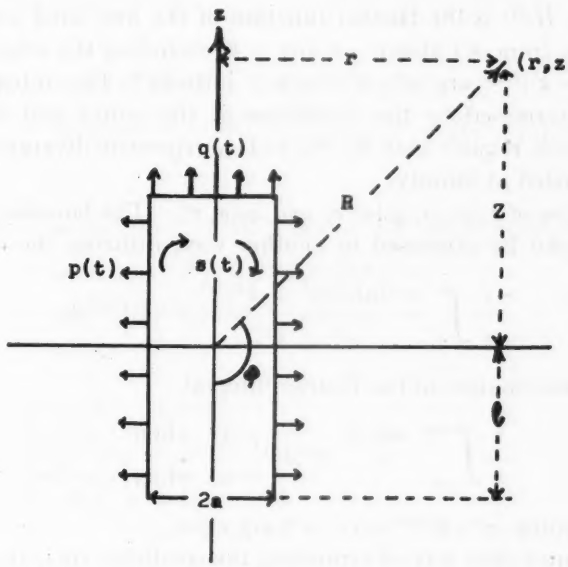

FIG. 1. Source of disturbance.

$$\widehat{rr} = \lambda\nabla^2\Phi_0 + 2\mu\frac{\partial}{\partial r}\left(\frac{\partial\Phi_0}{\partial r} - \frac{\partial^2\Theta_0}{\partial r\partial z}\right),$$

$$\widehat{rz} = \mu\frac{\partial}{\partial r}\left(2\frac{\partial\Phi_0}{\partial z} + \nabla^2\Theta_0 - 2\frac{\partial^2\Theta_0}{\partial z^2}\right),$$

$$\widehat{zz} = \lambda\nabla^2\Phi_0 + 2\mu\frac{\partial}{\partial z}\left(\frac{\partial\Phi_0}{\partial z} + \nabla^2\Theta_0 - \frac{\partial^2\Theta_0}{\partial z^2}\right), \tag{4}$$

$$\widehat{r\theta} = \mu\left(\frac{\partial^2\chi_0}{\partial r^2} - \frac{1}{r}\frac{\partial\chi_0}{\partial r}\right),$$

$$\widehat{z\theta} = \mu\frac{\partial^2\chi_0}{\partial r\partial z}.$$

It is now assumed that Φ_0, Θ_0 and χ_0 can be expressed as the *real parts* of the following integrals,

$$\Phi_0 = \int_0^\infty e^{ikVt}dk\int_C f_0(\sigma, k)H_0^{(1)}(\sigma r)e^{z(\sigma^2-k^2)^{\frac{1}{2}}}d\sigma,$$

$$\Theta_0 = \int_0^\infty e^{ikVt}dk\int_C g_0(\sigma, k)H_0^{(1)}(\sigma r)e^{z(\sigma^2-k^2)^{\frac{1}{2}}}d\sigma, \tag{5}$$

$$\chi_0 = \int_0^\infty e^{ikVt}dk\int_C n_0(\sigma, k)H_0^{(1)}(\sigma r)e^{z(\sigma^2-k^2)^{\frac{1}{2}}}d\sigma,$$

where $kV = hv$, $H_0^{(1)}$ is the Hankel function of the first kind and zero*th* order,[5] and C is a loop from ∞i about $-h$ and $-k$, excluding the origin and such that $\arg.\sigma = \arg.(\sigma^2-k^2)^{1/2} = \arg.(\sigma^2-h^2)^{1/2} = \pi/2$ initially.[6] The integrands in equations 5 are determined by the conditions at the source and by Sommerfeld's conditions[7] which require that Φ_0, Θ_0 and χ_0 represent divergent wave systems which are bounded at infinity.

Determination of $f_0(\sigma, r)$, $g_0(\sigma, r)$ *and* $\eta_0(\sigma, r)$.—The boundary conditions (1) at the source can be expressed in another way, utilizing the contour integral,

$$\frac{i}{\pi}\int_C \frac{\sigma \sinh l(\sigma^2 - k^2)^{1/2}}{\sigma^2 - k^2} e^{z(\sigma^2-k^2)^{1/2}} d\sigma,$$

which is a transformation of the Fourier integral,

$$\frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{\sin l\tau}{\tau} e^{iz\tau} d\tau \begin{cases} = 1, & \text{when } |z| < l, \\ = 0, & \text{when } |z| > l, \end{cases}$$

under the mapping $(\sigma^2-k^2)^{1/2} = i\tau, -\pi \leqq \arg.\tau \leqq 0$.

Thus, an equivalent way of expressing the condition (1a), at the source, is,

$$[-\widehat{rr}] = p(t)\frac{i}{\pi}\int_C \frac{\sigma \sinh l(\sigma^2 - k^2)^{1/2}}{\sigma^2 - k^2} e^{z(\sigma^2-k^2)^{1/2}} d\sigma.$$

Let the time factor $p(t)$ be expressible as the *real part* of the Fourier integral,

$$\int_0^\infty p_1(k) e^{ikVt} dk.$$

Thus the conditions (1) at the source are equivalent to the following;

$$\begin{bmatrix} -\widehat{rr} \\ -\widehat{rz} \\ -\widehat{r\theta} \end{bmatrix} = \frac{i}{\pi}\int_0^\infty \begin{bmatrix} p_1(k) \\ q_1(k) \\ s_1(k) \end{bmatrix} e^{ikVt} dk \int_C \frac{\sigma \sinh l(\sigma^2 - k^2)^{1/2}}{\sigma^2 - k^2} e^{z(\sigma^2-k^2)^{1/2}} d\sigma, \tag{6}$$

where $p_1(k)$, $q_1(k)$, and $s_1(k)$ are proportional to one another.

The stresses at the source can be represented by means of equations (4), in terms of the potentials Φ_0, Θ_0, and χ_0. The set of expressions so obtained must be exactly equivalent to the set (6). Equating the integrands, and solving for f_0, g_0 and n_0, the following results are obtained:

$$f_0 = -\frac{i\sigma \sinh l(\sigma^2 - k^2)^{1/2}}{\pi(\sigma^2 - k^2)} \cdot \frac{M_1}{N_1}, \tag{7a}$$

[5] Cf. E. Jahnke and F. Emde, *Tables of Functions* (4th ed.); New York: Dover, (1945), pp. 133 ff.

[6] If $f_0 = -\sigma/2(\sigma^2-k^2)^{1/2}$, the contour C can be deformed into the real axis and the integration with respect to σ yields Sommerfeld's classic representation of the Hertzian oscillator exp. $(ikR)/R$.

[7] A. Sommerfeld, "Die Greensche Funktion der Schwingungsgleichung," *Jahresb. Deut. Math. Verein.*, 21, 309–353 (1912).

where

$$M_1 = p_1(k)\mu\sigma(2\sigma^2 + h^2 - 2k^2)H_1^{(1)}(\zeta a) - 2q_1(k)\mu\sigma(\sigma^2 - k^2)^{1/2}\zeta\left[H_0^{(1)}(\zeta a) - H_1^{(1)}(\zeta a)/\zeta a\right],$$

and

$$N_1 = -\mu\sigma(2\sigma^2 + h^2 - 2k^2)(2\mu\sigma^2 + \lambda k^2)H_1^{(1)}(\zeta a)H_0^{(1)}(\sigma a) + 4\mu^2\sigma^2(\sigma^2 - k^2)\zeta H_1^{(1)}(\sigma a)H_0^{(1)}(\zeta a) + 2\mu^2h^2\sigma^2H_1^{(1)}(\zeta a)H_1^{(1)}(\sigma a)/a,$$

with

$$\zeta = (\sigma^2 + h^2 - k^2)^{1/2}.$$

$$g_0 = \frac{i\sigma \sinh l(\sigma^2 - h^2)^{1/2}}{\pi(\sigma^2 - h^2)} \cdot \frac{M_2}{N_2}, \tag{7b}$$

where

$$M_2 = -2p_1(k)\mu\sigma(\sigma^2 - h^2)^{1/2}H_1^{(1)}(\eta a) + q_1(h)\mu\sigma(2\sigma^2 - h^2)H_0^{(1)}(\eta a)/\eta - 2q_1(k)\mu\sigma H_1^{(1)}(\eta a)/a,$$

and

$$N_2 = -\mu^2\sigma^2(2\sigma^2 - h^2)^2H_1^{(1)}(\sigma a)H_0^{(1)}(\eta a) + 4\mu^2\sigma^3(\sigma^2 - h^2)H_1^{(1)}(\eta a)H_0^{(1)}(\sigma a) + 2\mu^2\sigma^2h^2H_1^{(1)}(\sigma a)H_1^{(1)}(\eta a)/a,$$

with

$$\eta = (\sigma^2 - h^2 + k^2)^{1/2},$$

$$n_0 = \frac{-is_1(k) \sinh l(\sigma^2 - h^2)^{1/2}}{\pi\mu\sigma(\sigma^2 - h^2)H_2^{(1)}(\sigma a)}. \tag{7c}$$

Equations (7) with (2), (3), (4) and (5), comprise the exact solution of the problem of a cylindrical source of finite length with prescribed forces acting on the walls.

At distances from the source large compared with the dimensions of the source, f_0, g_0 and n_0 can be expanded in terms of the parameters a and l. Retaining only the predominant terms in the expansions, we get,

$$f_0 \simeq \frac{p_1(k)\Delta\sigma}{8\pi\mu(\sigma^2 - k^2)^{1/2}}\left(\frac{2\sigma^2}{h^2} + 1 - \frac{2v^2}{V^2}\right) + \frac{q_1(k)A\sigma}{8\pi\mu h^2}, \tag{8a}$$

$$g_0 \simeq \frac{p_1(k)\Delta\sigma}{4\pi\mu h^2} + \frac{q_1(k)A\sigma}{8\pi\mu h^2(\sigma^2 - h^2)^{1/2}}, \tag{8b}$$

$$n_0 \simeq \frac{s_1(k)\Delta\sigma}{8\pi\mu(\sigma^2 - h^2)^{1/2}}, \tag{8c}$$

where Δ = volume of the source $= 2\pi a^2 l$, and A = area of vertical walls of source $= 4\pi a l$.

The actual particle displacements in the radiated field are obtained by inserting (5) into (3) and substituting the values of f_0, g_0 and n_0 from (7) or, at large distances from the source, from (8). Thus the radial component becomes

$$u = -\int_C \sigma f_0 H_1^{(1)}(\sigma r) e^{z(\sigma^2-k^2)^{1/2}} d\sigma + \int_C \sigma(\sigma^2 - h^2)^{1/2} g_0 H_1^{(1)}(\sigma r) e^{z(\sigma^2-k^2)^{1/2}} d\sigma,$$

where the integration with respect to k has been omitted. If r is so large that $|\sigma r| \gg 0$ at all points of the contour C, $H_1^{(1)}(\sigma r)$ can be replaced by its asymptotic expansion. Retaining only the first term of the expansion, it is found that

$$u = -e^{-3\pi i/4}\mu(\pi r)^{-1/2}\int_C (2\sigma)^{-1/2} f_0 e^{z(\sigma^2-k^2)^{1/2}+i\sigma r} d\sigma$$

$$+ e^{-3\pi i/4}\mu(\pi r)^{-1/2}\int_C (2\sigma)^{-1/2}(\sigma^2 - h^2)^{1/2} g_0 e^{z(\sigma-h^2)^{1/2}+i\sigma r} d\sigma.$$

Debye's Method of Steepest Descent[8] yields for the asymptotic expansion of these integrals,

$$-\frac{2k\cos\phi}{R} f_0(\sigma_1) e^{-ikR} - \frac{2ih^2\cos^2\phi}{R} g_0(\sigma_2) e^{-ihR}, \tag{9}$$

where R is the radial distance of the point (r, z) from the source, and ϕ is the angle made by the radius vector to this point with the negative z-axis (Figure 1), i.e., $R^2 = r^2 + z^2$, $\tan\phi = r/z$, σ_1 is the saddle point $-k\sin\phi$ (with $(\sigma^2 - k^2)^{1/2} = +k\cos\phi$), and σ_2, the saddle point $-h\sin\phi$ (with $(\sigma^2 - h^2)^{1/2} = +h\cos\phi$). At large distances from the source, f_0 and g_0 take the forms defined by equations (8). Substituting these values into (9) and applying the operator $\int_0^\infty - - e^{ikVt} dk$ (real part), the following expression valid at large distances from the source is obtained,

$$u = \frac{\Delta\sin\phi}{4\pi\mu VR}\left(1 - \frac{2v^2\cos^2\phi}{V^2}\right)\frac{d}{dt}\left[p\left(t - \frac{R}{V}\right)\right]$$

$$- \frac{Av^2\sin\phi\cos\phi}{4\pi\mu V^2 R} q\left(t - \frac{R}{V}\right)$$

$$+ \frac{\Delta\sin\phi\cos^2\phi}{2\pi\mu vR}\frac{d}{dt}\left[p\left(t - \frac{R}{v}\right)\right] + \frac{A\sin\phi\cos\phi}{4\pi\mu R} q\left(t - \frac{R}{v}\right), \tag{10}$$

[8] *Cf.* E. T. Copson, *Introduction to the Theory of Functions of a Complex Variable* (London: Oxf. Univ. Press, 1935), pp. 330 ff.

where

$$q\left(t - \frac{R}{v}\right) = \text{Rl.} \int_0^\infty q_1(k) e^{ikV(t-R/v)} dk, \tag{11}$$

and

$$\frac{d}{dt}\left[p\left(t - \frac{R}{V}\right)\right] = \text{Rl.} \int_0^\infty p_1(k) ikV e^{ikV(t-R/V)} dk.$$

In a similar manner, the corresponding expressions for v and w are obtained. On inspection, these expressions are seen to be composed of three separate wave systems, a P-wave (u_P, o, w_P) propagated with phase velocity V, a vertically polarized shear wave (u_{SV}, o, w_{SV}) and a horizontally polarized shear wave (o, v_{SH}, o), both of which are propagated with phase velocity v. Thus,

$$u = u_P + u_{SV},$$
$$w = w_P + w_{SV},$$
$$v = v_{SH}.$$

Putting

$$F_1(\phi) = \Delta(1 - 2v^2 \cos^2 \phi/V^2)/4\pi\mu V, \tag{12a}$$
$$G_1(\phi) = -Av^2 \cos \phi/4\pi\mu V^2, \tag{12b}$$
$$F_2(\phi) = \Delta \sin 2\phi/4\pi\mu v, \tag{12c}$$
$$G_2(\phi) = A \sin \phi/4\pi\mu, \tag{12d}$$
$$K(\phi) = \Delta \sin \phi/4\pi\mu v, \tag{12e}$$

the P-wave becomes,

$$\begin{bmatrix} u_P \\ w_P \end{bmatrix} = \left[\frac{F_1(\phi)}{R} \frac{d}{dt}\{p(t - R/V)\} + \frac{G_1(\phi)}{R} q(t - R/V)\right] \begin{bmatrix} \sin \phi \\ -\cos \phi \end{bmatrix}, \tag{13a}$$

the SV-wave,

$$\begin{bmatrix} u_{SV} \\ w_{SV} \end{bmatrix} = \left[\frac{F_2(\phi)}{R} \frac{d}{dt}\{p(t - R/v)\} + \frac{G_2(\phi)}{R} q(t - R/v)\right] \begin{bmatrix} \cos \phi \\ \sin \phi \end{bmatrix}, \tag{13b}$$

the SH-wave,

$$v_{SH} = \frac{K(\phi)}{R} \frac{d}{dt}\{s(t - R/v)\}. \tag{13c}$$

The coefficients (12) which enter into equations (13) and describe the angular variation of the amplitude of the radiated P, SV, and SH waves with the angle ϕ, are graphed in Figures 2–4.

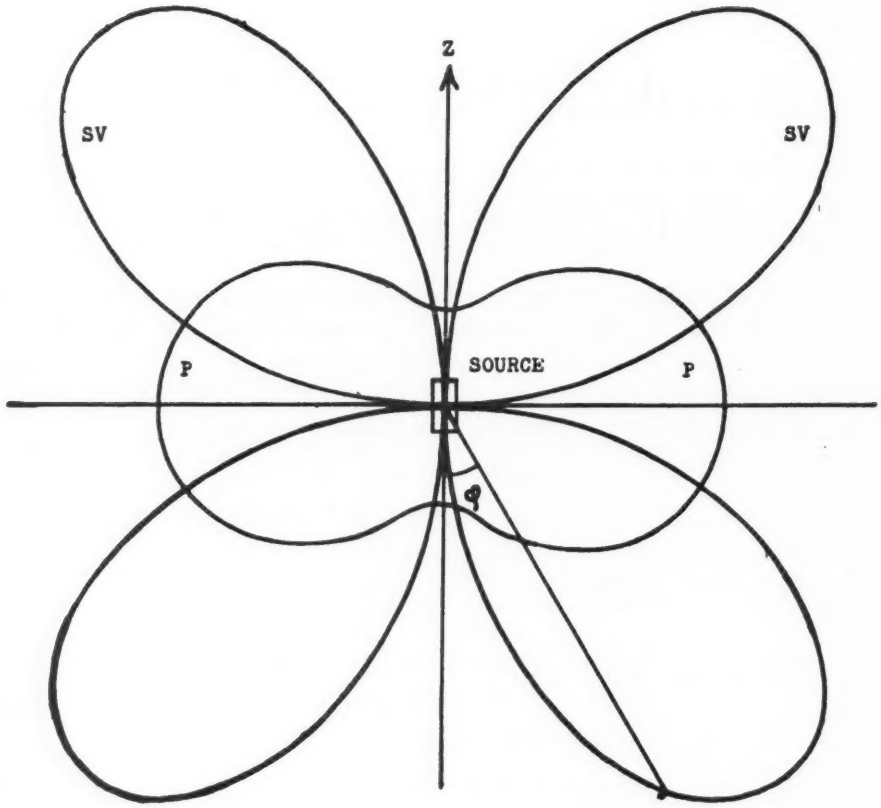

FIG. 2. Variation of P and SV amplitudes with ϕ, when the source is subjected to a pressure $p(t)$ only. Radii in the figure are proportional to $F_1(\phi)$ (in the case of P), and to $F_2(\phi)$ (in the case of SV) *cf.* equations 12a, 12c, 13a and 13b.

Energy radiated from the source in P, SV, and SH.—If Φ_{ij} is the stress tensor of the radiating field, u_j the components of the particle displacement, then, the rate of flow of energy per unit area in the direction of the unit vector n_i is

$$-\sum_j n_i \Phi_{ij} \frac{d\mu_j}{dt} .$$

Integrating this formula over the infinite sphere and also throughout the duration of the disturbance, the total energy of the different waves is obtained. For the P-wave, the total energy E_P is the sum of two parts, E_P' due to the lateral pressure $p(t)$ acting on the source, and E_P'' due to the shearing stress $q(t)$. Thus,

$$E_P = E_P' + E_P''$$

where

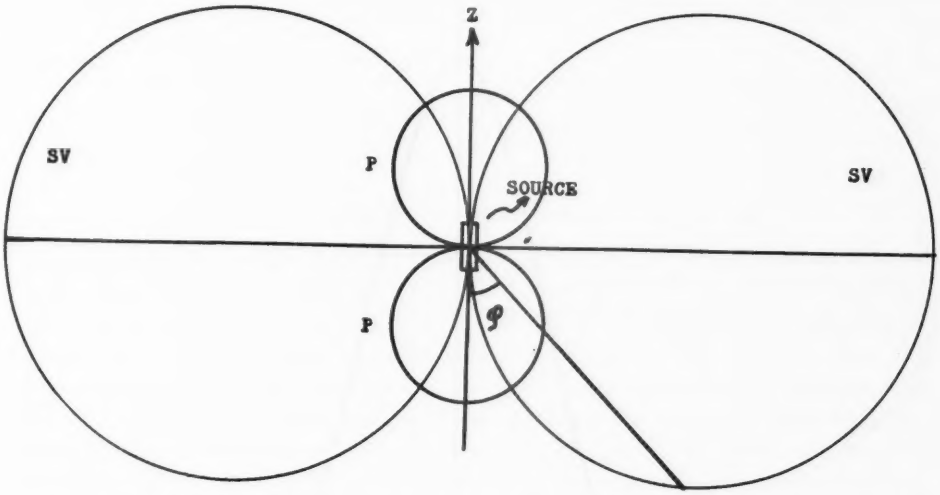

FIG. 3. Variation of P and SV amplitudes with ϕ, when the source is subjected to shearing stress $q(t)$ only. Radii are proportional to $G_1(\phi)$ (in the case of P), and to $G_2(\phi)$ (in the case of SV); *cf.* equations 12b, 12d, 13a, and 13b.

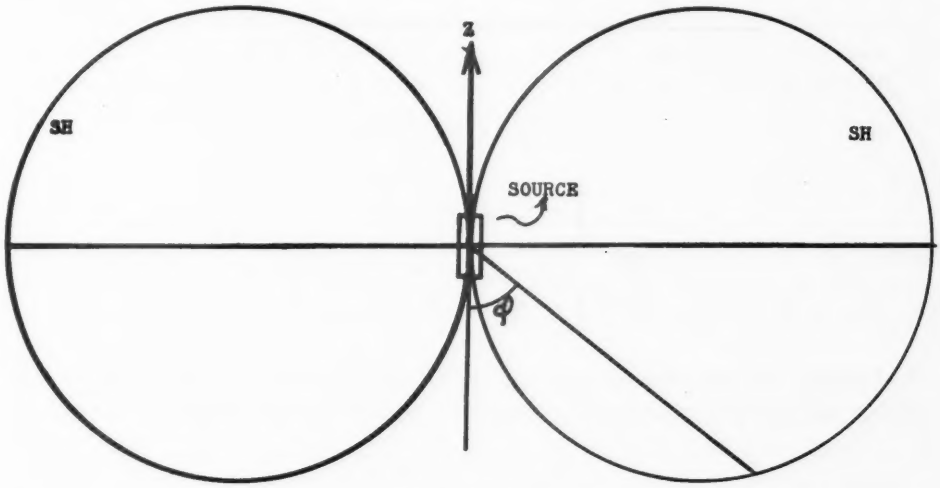

FIG. 4. Variation of SH amplitude with ϕ, when the source is subjected to a horizontal shearing stress $s(t)$ only. Radii are proportional to $K(\phi)$; *cf.* equations 12e and 13c.

$$E_P' = \frac{\Delta^2 P^2}{4\pi\mu V^3}\left(\frac{2v^2}{5V^2} + \frac{V^2}{2v^2} - \frac{2}{3}\right),$$

$$E_P'' = A^2 Q^2 v^2 / 12\pi\mu V^3,$$

and

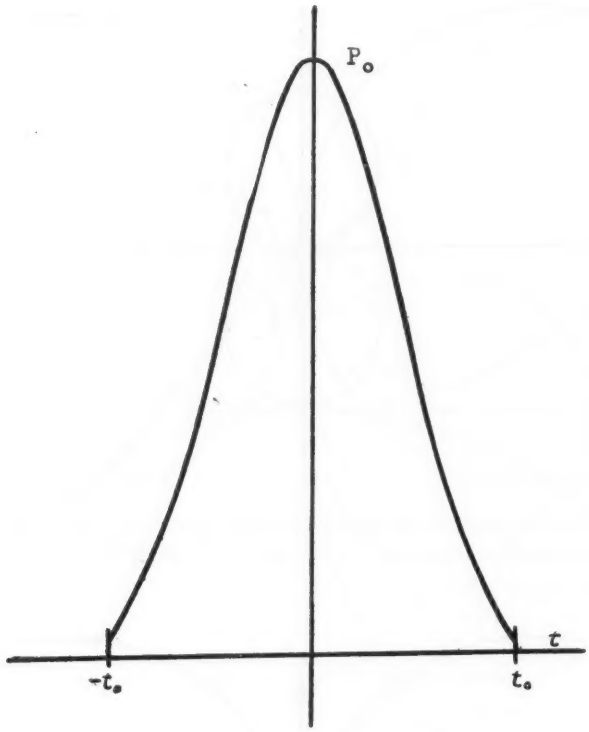

FIG. 5. $p(t)=P_0 \exp.(-\pi t^2/t_0^2)$.

$$P = \int_{-\infty}^{+\infty} [p''(t)]^2 dt,$$

$$Q = \int_{-\infty}^{+\infty} [q'(t)]^2 dt.$$

For SV, the total energy E_{SV} is similarly constituted, E_{SV}' being due to the lateral pressure $p(t)$ at the source, and E_{SV}'' to the shearing stress $q(t)$. Thus,

$$E_{SV} = E_{SV}' + E_{SV}''$$

where

$$E_{SV}' = 2\Delta^2 P^2/15\pi\mu v^3,$$

and

$$E_{SV}'' = A^2 Q^2/6\pi\mu v.$$

The energy of SH is due entirely to the horizontal shearing stress $s(t)$ acting at the source, and is,

$$E_{SH} = \Delta^2 S^2 / 6\pi\mu v^3,$$

where

$$S = \int_{-\infty}^{+\infty} [s''(t)]^2 dt.$$

DISCUSSION OF RESULTS

We have tried to reproduce, in mathematical form, the disturbance generated by the detonation of a charge in a cylindrical shot hole. The quantities a and l are not the physical dimensions of the bore hole in which the charge is detonated. Conditions in the immediate neighborhood of the shot hole are such that the assumptions upon which our work is founded, in particular the assumption of infinitesimal strain, are not verified in this domain. These quantities correspond rather to the dimensions of Sharpe's "equivalent cavity."[9] This is the smallest surface about the shot hole beyond which the medium is "perfectly elastic" to the disturbance. Morris[10] says that it is "determined by the position at which no further work is done on the medium by the shock wave." The form of the "equivalent cavity" determines to a large extent the characteristics of the elastic waves generated by the source.

The partition of energy between the dilatational and shear waves generated by the application of a lateral pressure $p(t)$ to the walls of a cylindrical source is a problem of special interest as it represents the ideal case of a charge detonated in a shot hole. In this case,

$$\frac{E_P'}{E_{SV}'} = \frac{v^3}{V^3}\left(\frac{3v^2}{2V^2} + \frac{15V^2}{8v^2} - \frac{5}{2}\right). \tag{14}$$

For a Poisson solid, (14) implies that approximately 60 percent of the energy goes into SV and only 40 percent into P. Moreover SV is beamed in directions making angles of 45° with the axis of the source (see Fig. 2), with maximum amplitude 1.6 times the maximum amplitude of P.

These results at first sight cause some surprise. It has often been said that artificial disturbances generate little shear energy.[11] Actually this is not always the case. Wiechert, Brockamp, Wölcken, Jeffreys and others have reported shear waves of large amplitude present in the seismograms of large explosions. Seismograms of local blasts occurring within, say, 20 km of Florissant often contain a powerful SV phase. Whether this phase is of primary origin, originating at the actual source, or of secondary origin, due to a change in type somewhere along

[9] J. A. Sharpe, "The Production of Elastic Waves by Explosion Pressures: 1. Theory and Empirical Field Observations," *Geophysics* VII (1942), 144–154.

[10] G. Morris, "Some Considerations of the Mechanism of the Generation of Seismic Waves by Explosives," *Geophysics*, XV (1950), 61–69.

[11] *Cf.* H. Jeffreys, *Reports on Progress in Physics*, 10 (1944–1945), 79.

the trajectory of the ray, is still not clear. The theory given in this paper indicates, at any rate, that this SV phase is actually of primary origin. Moreover the theory shows that a characteristic of this wave is that it is channelled in certain directions. The low intensity of shear waves on some blast records may be merely indicative that the seismometer is located outside the range at which the SV-cone of energy reaches the surface. Little use so far has been made of shear waves in seismic prospecting, as their late arrivals are usually obscured by much background noise. Should it be practicable, however, to use these waves, the existence of the beamed SV-wave might prove to be of some importance.

The absolute magnitude of the total energy radiated by the action of the pressure $p(t)$ is, as we have seen, proportional to

$$P = \int_{-\infty}^{+\infty} [p''(t)]^2 dt.$$

The total amount of radiated energy depends in this case upon the double rate of change of the applied stress. Assuming that

$$p(t) = P_0 \exp(-\pi t^2/t_0^2) \text{ (see Fig. 5)},$$

then

$$P = 3P_0\pi^2 2^{-\frac{1}{2}} t_0^{-3};$$

and thus,

$$E_P' = \frac{3\pi\Delta^2 P_0^2}{2^{1/2}\mu V^3 t_0^3}\left(\frac{v^2}{5V^2} + \frac{V^2}{4v^2} - \frac{1}{3}\right),$$

where Δ = volume of the "equivalent cavity," P_0 = maximum pressure at the source.

E_P', E_{SV}' and E_{SH}, being proportional to t_0^{-3} increase very rapidly with decrease in the duration of the impulse. Moreover, the total energy radiated by such a source is proportional to the product ΔP_0. The observations of Sharpe[12] and Morris[12] help to confirm these conclusions.

[12] *Op. cit.*

EDITORIAL

ARE WE USING OUR FREEDOMS?*

CURTIS H. JOHNSON†

Recent national and international political events have focussed our attention on our freedoms. The probable removal of many governmental restrictions implies that domestically an era of especially free economy is about to begin. Even behind the iron curtain there is the possibility of a change for the first time in several decades.

In our part of the world we have inherited a free society in which to do our work. Freedom to think and say what we please—to freely exchange ideas. Freedom to come and go—to let our search for oil carry us where it will. Freedom to direct or expand our investigations along paths of our choosing. We have the immeasurable benefit of working under a system of free enterprise and free industrial expansion based on a free market.

We dare not take all this freedom for granted. It is a precious thing which must be tended carefully to live. Our preoccupation with our science—with oil-finding itself—must not prevent our participation as good citizens in every activity which will keep us in the light of freedom.

Are we truly using our freedom to its full extent in our oil-finding efforts? Are we taking full advantage of the unlimited scope of action and thought our freedom allows?

Every so often it pays any man or group of men to roll up their sleeves, hitch up their suspenders and dig in for a new start. Oil-finders—geologists, geophysicists, and paleontologists—are no exception. The very fact that we are continuing to find oil in adequate quantities as we have in the past may tend to make us complacent, make us content with the same old rut.

As oil-finders we are more fortunate than we realize. Rarely do we stop to think that not only do we live in a free society as a whole, but that most of our employers or clients offer us complete freedom to exercise our imagination and perform with originality in the finding of oil.

Decentralization, delegation of responsibility, and removal of hampering restrictions are the new watch-words of the modern oil industry. We, as front-line shock-troops in the oil-finding campaign, must catch this spirit—take advantage of these favorable working conditions.

The techniques, the types of thinking which have found us so many anticlinal oil fields must not dominate our current effort. The relative ease with which we have found oil in the past must not set the tempo for our present activity. Each man of us must tear off the inhibitions and habits of the past and free his latent abilities.

The freedom we enjoy is more than the heritage of our society. It is more than the enlightenment of our industry. It is, in the final analysis, in our individual attitudes and thinking that our true potentialities for freedom exist. Let us utilize our God-given individual freedom of original thinking; throw off our self-imposed shackles; and find oil as (and where) we've never found it before.

* Printed as guest editorial in *World Oil* for April, 1953.

† General Petroleum Corporation, Los Angeles. Retiring President, Society of Exploration Geophysicists. Now with Geophysical Service Inc., Dallas.

ANNUAL SURVEY OF GEOPHYSICAL EDUCATION 1952–1953*

The shortage of professionally trained geophysical engineers, as of all types of engineers, continues to be acute. In spite of the encouraging growth of offerings in the field of geophysical education, the needs of industry, government, and the universities are such as to induce a degree of competition for available manpower that is far from healthy.

There has been no increase in the number of departments of geophysics and geophysical engineering over the seven reported last year. A total registration of 2,036 in geophysical courses reported by 41 educational institutions represents a decrease of 208 over the figures available at the corresponding time last year. The number of undergraduate students whose major field is geophysics or geophysical engineering is 273, a decrease of 17, and the number of graduate student majors is 174, a decrease of 16.

The total number of undergraduate degrees in geophysics or geophysical engineering given between July 1, 1951 and June 30, 1952 was 92, a decrease of 5 over last year's total. The number of master's degrees conferred in the same period was 34, an increase of 4. Doctor's degrees in geophysics conferred in this same period were as follows:

California Institute of Technology	1
University of California (Berkeley)	1
Colorado School of Mines	4
Columbia University	1
Massachusetts Institute of Technology	2
Saint Louis University	3
University of Toronto	7

The details of courses and administration in the 45 institutions which answered the questionnaire are given in the tables. In each case the number of semester or quarter courses on the elementary (E), advanced (A), and graduate (G) levels devoted exclusively to the given field and actually taught in the summer of 1952 or the year 1952–1953 are given under the respective column headings.

* Presented at the Annual Business Meeting of the Society at Houston, March 23, 1953 by Reverend James B. Macelwane, S.J., chairman of the Education Committee. The other members of the committee are D. C. Skeels, M. King Hubbert, Beno Gutenberg, Perry Byerly, John C. Hollister, Sherwin F. Kelly, and H. W. Straley III.

TABLE I

Institution	Administration		Students in Applied Geophysics				Titles of Geophysical Degrees	Degrees Conferred July 1951–June 1952			Faculty Teaching Courses in Geophysics
	Departments	Schools or Colleges	Total in Courses 1952–1953		Majors			Bachelors	Masters	Doctors	
			I	II	Undergraduate	Graduate					
Brigham Young U.	Geology & Engineering Science[1]	Arts & Sciences	—	—	—	—	—	—	—	—	1
Brown U.	Oceanography	—	3	3	—	—	—	—	—	—	1
Calif. Inst. of Tech.	Division of Geological Sciences	—	15	16	2	14	M.S., Ph.D.	—	1	1	5
Calif., U. of (Berkeley)	Geological Sciences	Letters & Science	35	35	14	11	A.B., M.A., Ph.D.	4	—	1	2
Colorado Sch. of Mines	Geophysics	—	132	206	109	14	Geophysical Engineer, M.S., D.Sc.	40[2]	3	4	4
Colorado, U. of	Geology	Arts & Sciences	35	—	—	—	—	—	—	—	1
Columbia U.	Geology	Graduate Faculty	15	15	—	13	M.A., Ph.D.	—	3	1	3
Cornell U.	Geology	(?)	(?)	(?)	—	—	—	—	—	—	1
Dalhousie U.	Physics	Faculty of Arts & Sciences	—	—	—	1	B.S.,[3] M.S.	—	—	—	1
Franklin & Marshall Col.	Geology	—	—	—	—	—	B.S.[4]	—	—	—	1
Illinois, U. of	Geology & Mining Engineering	Liberal Arts & Sciences, Engineering	21	—	—	—	—	—	—	—	1
Iowa State Col.	Physics, Civil Engineering	—	27[5]	16[5]	—	1	B.S.,[6] M.S.,[6] Ph.D.[6]	—	1	—	2
Johns Hopkins U.	Geology	—	—	12	—	—	—	—	—	—	1
Kansas State Col.	Physics	Arts & Sciences	4	8	4	—	B.S.[7]	1	—	—	1
Lehigh U.	Mining Engineering	Engineering	7	6	8	—	B.S.[8]	3[9]	1[10]	—	1
Mass. Inst. of Tech.	Geology & Geophysics	—	13	33	20	14	B.S.,[11] Ph.D.[11]	8	—	2	3
Miami U.	Geology	Arts & Sciences	9	—	—	—	—	—	—	—	1
Michigan Col. of M. & T.	Physics	—	25	30	—	1	M.S.[12]	—	4	—	2
Michigan, U. of	Geology, Civil Engineering	Literature, Science & Arts	30	12	—	3	M.S., Ph.D.	—	2	—	1
Minnesota, U. of	Geophysics	School of Mines, Institute of Technology	46	31	1	2	Bachelor of Geophysics,[13] M.S.	—	1	—	1
Mississippi State Col.	Physics	Science	—	16	—	—	—	—	—	—	1
Montana Sch. of Mines	Physics	—	—	8	—	—	—	—	—	—	1
New Mex. Inst. of M. & T.	Physics & Geophysics	—	2	7	4	7	B.S.,[14] M.S.[14]	—	2	—	2
New York U.	Geology	Graduate School of Arts & Sciences	9	7	—	—	—	—	—	—	1
North Carolina, U. of	Geology & Geography	Arts & Sciences	1[15]	4[15]	—	—	—[16]	—	—	—	1
North Dakota, U. of	Geology	Engineering	—	10	—	—	—	—	—	—	1
Northwestern U.	Geology & Civil Engineering	Liberal Arts, Technological Institute	15	17	—	—	—	—	—	—	3
Ohio State U.	Geology	Arts & Sciences	—	12	—	—	—	—	—	—	1
Oklahoma, U. of	Physics, Geology	Arts & Sciences	88	117	—	1	—	3[17]	—	1[18]	2
Oregon State Col.	Geology & Physics	Science	—	5	—	—	—	—	—	—	2
Pennsylvania State Col.	Division of Geophysics & Geochemistry, Civil Engineering	Mineral Industries	62	87	15	17	B.S., M.S., Engineer of Mines, Ph.D.	2	2	—	6

TABLE I—*Continued*

Institution	Administration		Students in Applied Geophysics				Titles of Geophysical Degrees	Degrees Conferred July 1951–June 1952			Faculty Teaching Courses in Geophysics
	Departments	Schools or Colleges	Total in Courses 1952–1953		Majors			Bachelors	Masters	Doctors	
			I	II	Undergraduate	Graduate					
Pittsburgh, U. of	Geology	The College	29	30	—	—	—	—	—	—	1[19]
Rensselaer Poly. Inst.	Fuel Resources	—	6	6	2	2	B.S., M.S.,[20] Ph.D.	—	—	—	2
Saint Louis U.	Geophysics & Geophysical Engineering	Institute of Technology, Graduate	92	132	47	17	B.S.,[21] M.S., Ph.D.	10	7	3	11
Southern Methodist U.	Geology	Arts & Sciences	1	—	—	—	—	—	—	—	1
Texas A. & M. Col.	Geology, Physics, Oceanography	Engineering & Science, Arts & Sciences	60	73	9	26	B.S.,[22] M.S.,[23] Ph.D.[23]	4	1	—	14
Texas Christian U.	Physics	—	15	—	—	—	—	—	—	—	1
Toronto, U. of	Physics	—	35	33	11	11	B.A., M.A., B.A.Sc.,[24] M.A.Sc.,[24] Ph.D.	6	5	7	3
Tulane U.	Geology	Arts & Sciences	14	15	—	—	—	—	—	—	1
Tulsa, U. of	Physics & Geophysics	Engineering, Liberal Arts	18	47	15	1	B.S.[25]	11	1	—	1
Utah, U. of	Geophysics	Mines & Mineral Industries	14	31	9	4	B.S.,[26] M.S.,[26] Ph.D.[26]	3	—	—	2
Western Ontario, U. of	Physics, Geology	Arts & Sciences	4	4	—	—	B.Sc.,[27] M.Sc.,[28] Ph.D.[28]	—	—	2[29]	1
West Virginia U.	—	Mines	9	7	—	—	—	—	—	—	1
Williams Col.	Geology	—	—	17	—	—	—	—	—	—	1
Wisconsin, U. of	Geology	Letters & Science	25	45	3	14	B.S.,[30] M.S.,[30] Ph.D.[30]	—	—	—	1
Xavier U.	Physics	—	—	—	—	—	—	—	—	—	1

[1] Beginning Fall 1953.
[2] Geophysical Engineer.
[3] Engineering Physics.
[4] In Geology.
[5] Quarters—15 students, 3rd quarter.
[6] In Physics with Geophysics option.
[7] In Physical Science (Geophysics option).
[8] In Mining Engineering (Engineering Geophysics option).
[9] One in Mining Engineering, two in Engineering Physics.
[10] In Geology (Engineering option).
[11] In Geophysics.
[12] In Geophysics.
[13] Five year undergraduate curriculum.
[14] In Geophysics.
[15] Quarter—number for 3rd quarter not available.
[16] A degree in Geology with Geophysical emphasis may be obtained.
[17] In Physics with courses in Geophysics.
[18] In Physics with Geophysical research.
[19] Part-time.
[20] In Geophysics.
[21] (a) Geophysical Engineering; (b) Hydrological Engineering; (c) in Professional Geophysics.
[22] In Geology (Geophysics option).
[23] In Oceanography (Physical, Chemical, Biological, Geological & Meteorological).
[24] Of Applied Science.
[25] In Geophysical Engineering.
[26] In Geophysics.
[27] In Geology with Geophysics option.
[28] In Geology or Physics with Geophysical option.
[29] In Physics with theses on geophysical topics.
[30] In Geology (Geophysics option).

TABLE II

Institution	Field Covered by Courses																		
	General Geophysics	Geophysical Theory	Geophysical Exploration (Several Methods)	Seismic Exploration	Gravity Exploration	Magnetic Exploration (Including Airborne)	Geochemical Exploration	Electrical and Electromagnetic Exploration	Other Geophysical Methods of Exploration	Earthquake Seismology	Geo-Electricity	Geomagnetism	Geodesy (Cartography)	Geodesy (Gravity)	Geophysical Electronics	Hydrology	Physical Oceanography	Volcanology	Other
Brown U.																	2G		
Calif. Inst. of Tech.	3A	1A	1A						1A	1A						1A			3A
	3G	2G		2G															
Calif., U. of (Berkeley)			3A	2A						1A									
		1G								4G								1G	
Colorado Sch. of Mines		2E	2E																
		2A	1A	1A	1A	1A									1A				
		2G	1G	1G		1G													
Colorado, U. of	1E																		
Columbia U.	1G	1G	1G							1G				1G					
Cornell U.																	1E		
Franklin & Marshall Col.	1E															1E			
Illinois, U. of			1E																1A
																			1G
Iowa State Col.			1E													1A			2G
Johns Hopkins U.	1E																		
Kansas State Col.			1E																
Lehigh U.	1E		1E	½A	½A	½A		½A											
Mass. Inst. of Tech.		4G	1E	1E															1G
Miami U.			1E																
Mich. Col. of M. & T.		2A	1A						1A										
		1G																	
Michigan, U. of	3E		5A										(?)			(?)			
Minnesota, U. of	1E		1E	1A	½A	½A		1A		1E									1G
Mississippi State Col.			1E																
Montana Sch. of Mines	1E																		
New Mex. Inst. M. & T.	1A	1G	2G																
New York U.	6G																		
North Carolina, U. of	1E					1A		1A										1E	
North Dakota, U. of	1E																		
Northwestern U.	2E															2E			
Ohio State U.	3E												3A	6A					
														3G					
Oklahoma, U. of		½A*	2½A*																
Oregon State Col.	1E																		
Pennsylvania State Col.	1E																		
	1A	1A	4A				1A		1A							2E†			
	1G	1G								1G									6G
Pittsburgh, U. of			2E																
Rensselaer Poly. Inst.	1E		1A	1A															
			1G																
Saint Louis U.	1A	2A	4A							5A						2A			1A
	4G	1G			1G	1G				1G									
Southern Methodist U.			1E‡																
Texas A. & M. Col.		1E	1E												1E				
				1A													2A		3A
																	7G		11G
Texas Christian U.	1E																		
Toronto, U. of	1E		1E										1E						
	1A	1A	1A										1A						
	1G		1G																
Tulane U.	1E	1E	1E	1E	1E	1E		1E											
	1A																		
Tulsa, U. of	2E			2A	2A	2A		2A							1E				
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West Virginia U.			1E			1E				2E									
Williams Col.	1E																		
Wisconsin, U. of	1E		1E													1E	1E		
	1G																		

* One Course (the ½'s) may count graduate credit.
† In Civil Engineering Department.
‡ Could also be classified General Geophysics.

PATENTS

O. F. RITZMANN*

GRAVIMETRIC PROSPECTING

U. S. No. 2,626,525. C. A. Heiland. Iss. 1/27/53. App. 7/8/46.

Apparatus for Aerogravimetric Prospecting. A gravimeter which may be lowered to the ground from a helicopter or blimp by a cable and having a base plate on which the instrument is automatically leveled by pendulum-controlled servo-motors, the location being determined by observers sighting on the aircraft from three ground points.

U. S. No. 2,627,727. C. F. Sellers. Iss. 2/10/53. App. 10/22/46. Assign. Robt. H. Ray, Inc.

Geophysical Prospecting Device. A diving bell for a geophysical instrument and its operator having an inner operating chamber closed by a top cover plate, an annular floodable chamber to which compressed air may be supplied, and a bottom skirt under which compressed air is supplied to break mud suction when the bell is lifted.

MAGNETIC PROSPECTING

U. S. No. 2,624,778. G. J. Perlow and E. R. Haberland. Iss. 1/6/53. App. 10/25/45.

Electronic Fluxmeter and Alternating Current Amplifier. A magnetic gradiometer having a pair of spatially-separated opposing coils which are moved in the magnetic field, the emf generated being chopped, amplified, synchronously rectified, integrated and recorded.

U. S. No. 2,624,783. V. A. Nedzel. Iss. 1/6/53. App. 6/4/45. Assign. U.S.A.

Apparatus and Method for Measuring Magnetic Flux. A rotating-coil fluxmeter having a rigidly-attached second coil which is rotated in a known variable field and with the difference between the emfs induced in the coils detected and amplified so that the known field may be adjusted to equalize the emfs.

U. S. No. 2,626,308. O. H. Schmitt. Iss. 1/20/53. App. 8/7/44. Assign. U.S.A.

Method of Magnetic Investigation. A method of investigating the field of a magnetic model by using for the model three separately-energized mutually-perpendicular coils excited by a-c and measuring the voltage induced in an exploring coil.

U. S. No. 2,627,542. T. Koulomzine. Iss. 2/3/53. App. 8/21/51.

Magnetometer. A device for measuring the gradient of the vertical component of a magnetic field and having a spring-suspended float immersed in a liquid with a vertical magnet in the float below its center of buoyancy and graduations for observing elongations of the spring.

U. S. No. 2,627,727. C. F. Sellers. Iss. 2/10/53. App. 10/22/46. Assign. Robt. H. Ray, Inc.

Geophysical Prospecting Device. For abstract see Gravimetric Prospecting.

U. S. No. 2,628,502. N. E. Klein. Iss. 2/17/53. App. 5/11/44. Assign. U.S.A.

Magnetic Orientation. A magnetic orientation system for an air-driven gyro in which the rotating gyro also rotates an asymmetric magnetic vane passing through a coil coaxial with the gyro, the voltage induced in the coil being amplified and used to control air ports so that the air-escape reaction will provide gyro-orienting torques.

* Gulf Oil Corporation, Patent Department.

U. S. No. 2,629,003. F. Haalck. Iss. 2/17/53. App. 4/7/51 and 3/18/52. Assign. Askania-Werke A. G.

Magnetometer. A magnetic force-balance type of magnetometer having a pair of disc-shaped magnets which are axially suspended on a horizontal torsion wire with calibrated torsion heads at each end.

U. S. No. 2,632,796. W. H. Fenn. Iss. 3/24/53. App. 4/1/46. Assign. U.S.A.

Fluxmeter. A device for measuring flux density and having a D'Arsonval meter movement which is placed in the field and a current passed through it to produce a standard deflection, the current being measured by a separate ammeter in series with the movement.

U. S. No. 2,632,883. M. S. Richardson. Iss. 3/24/53. App. 7/7/44. Assign. U.S.A.

Magnetometer System. A magnetic detector having four flux-valves with their cores parallel and connected to an a-c source as four arms of a Wheatstone bridge circuit with the indicating circuit across the other diagonal of the bridge.

U. S. No. 2,632,884. P. M. Murphy. Iss. 3/24/53. App. 6/11/46.

Orienting Mechanism for Magnetic Detector Devices. A self-orienting total-field magnetometer in which the detecting elements are mounted in three gimbals arranged so that the innermost gimbal rotates through an angle twice that traversed by the outermost gimbal.

SEISMIC PROSPECTING

U. S. No. 2,614,804. C. H. Carlisle. Iss. 10/21/52. App. 1/29/49. Assign. Standard Oil Development Co.

Apparatus for Drilling Under Water. A device for drilling seismic shot holes in water-covered areas and using an expendable bit containing the explosive charge with the drilling mechanism retrievable by a cable to the boat.

U. S. No. 2,625,129. J. W. Flude. Iss. 1/13/53. App. 9/16/39, 3/7/42 and 5/28/47.

Buoy-Type Detector Carrier. A float for a detector cable used in marine seismic operations having a pair of sheaves on its under side through which the detector cable passes so that the detector is raised to the float when towed but is lowered to bottom in an upright position when the cable is slacked off.

U. S. No. 2,626,004. A. F. Hasbrook. Iss. 1/20/53. App. 1/19/50. Assign. Olive S. Petty.

Apparatus for Recording Time Intervals. A circuit for firing a seismograph shot in coincidence with a distinctive timing line in which firing of the shot is controlled by an impulse from a multivibrator operating on every tenth timing pulse and whose output is combined with that of the timing device to produce a distinctive timing line on the record.

U. S. No. 2,626,381. R. W. Olson. Iss. 1/20/53. App. 1/27/48. Assign. Texas Instruments Inc.

Variable Resistance Distributed Seismometer. A variable-impedance cable-like seismometer having two long conductors embedded in an electrically-conducting rubber matrix of oval cross-section and with a flexible insulating sheath, a current being passed from one conductor through the conducting rubber to the other conductor and to the input transformer of the amplifier.

U. S. No. 2,630,188. J. E. Hawkins and W. E. Pugh. Iss. 3/3/53. App. 1/11/47. Assign. Seismograph Service Corp.

System and Method of Generating Seismic Waves in the Earth. A method of seismic shooting in which explosive charges are arranged in an array of shot holes and fired at various depths or with various delay times to simulate a large shaped charge and direct the explosive force downward.

U. S. No. 2,632,150. D. Silverman, J. D. Eisler and C. C. Lash. Iss. 3/17/53. App. 2/23/49. Assign. Stanolind Oil and Gas Co.

Marine Seismic Surveying. A seismograph spread for marine operations which is adjusted for neutral buoyancy by means of automatically-controlled variable-volume floats on the cable so that the spread will remain at uniform depth behind a towing point between 5 and 15 feet below the surface of the water.

U. S. No. 2,632,520. A. J. Hintze. Iss. 3/24/53. App. 8/1/49. Assign. Phillips Petroleum Co.

Apparatus for Producing Seismic Waves in a Body of Water. A boat having a heavy flat bottom so that explosive charges may be fired in the boat against the bottom or a short distance above it and the bottom will impart the explosion impulse to the water.

U. S. No. 2,633,077. P. M. McDavid. Iss. 3/31/53. App. 8/3/50.

Counting Machine. A device for counting timing lines on seismograph records having an elastic band carrying type characters with an adjustment for stretching the elastic band to bring the spacing of the characters into coincidence with the proper timing lines and an inking pad so that the timing-line numbers may be printed on the record.

WELL LOGGING

Serial No. 78,333. H.-G. Doll. Published 1/13/53. App. 2/25/49. Assign. Schlumberger Well Surveying Corp.

Radioactive Shaped Charges. A radioactive marking device having a shaped explosive charge with a suitable radioactive material incorporated either in the explosive charge or in the liner or both.

U. S. Re. 23,621 (Original No. 2,552,428). A. B. Hildebrandt. Iss. 2/24/53. App. 9/21/49, 5/8/51 and 9/26/52. Assign. Standard Oil Development Co.

Sleeve Supported Electrode for Well Logging. An electric-logging electrode assembly having a spring-expanded sleeve of electrically-insulating material carrying on its outer surface electrodes which are pressed against the formation but which are insulated from the body of drilling fluid in the borehole.

U. S. No. 2,625,039. H. J. Wagner. Iss. 1/13/53. App. 9/30/48.

Apparatus for Detecting Seepage of Water into Wells. A water detector having a pair of spaced annular packer rings with a by-pass and a receptacle for collecting fluid entering the well between the packers, the receptacle having an electrical resistance element which is short circuited by entrance of water and the change in resistance indicated at the surface.

U. S. No. 2,625,374. L. J. Neuman. Iss. 1/13/53. App. 1/22/46.

Method of Controlling Fluid Infiltration. A method of measuring permeability of well formations in which the well is drilled with a positive potential on the drill as obtained from an electric generator whose other terminal is on the surface, running an electric log, then applying a negative potential to the drill for a short time, and again running the electric log.

U. S. No. 2,625,583. R. A. Broding. Iss. 1/13/53. App. 10/28/50. Assign. Schlumberger Well Surveying Corp.

Magnetic Induction Well-Logging Instrument. An electromagnetic well-logging apparatus in which a solenoid in the well is connected in a bridge circuit energized with two frequencies and the unbalance fed to two filters and phase discriminators which indicate the out-of-phase component of the low frequency and the in-phase component of the high frequency to simultaneously measure the magnetic susceptibility and electric conductivity of the formations.

U. S. No. 2,626,305. R. F. Krueger. Iss. 1/20/53. App. 12/12/49. Assign. Union Oil Co. of Calif.

Electric Logging with Oil Base Drilling Fluids. Apparatus for electric logging in the presence of oil-base mud in which an a-c field of about 100 volts per inch is applied to the mud in the region where electrical contact to the formation is desired so as to break down the dielectric effect and render the mud conducting.

U. S. No. 2,626,979. J. P. Woods. Iss. 1/27/53. App. 4/7/48. Assign. The Atlantic Refining Co.

Apparatus for Electrically Logging Boreholes. A four-electrode a-c logging system in which the energizing current is also passed through an automatically-controlled impedance which is adjusted so that the potential drop across the impedance equals the potential difference between the potential electrodes in the well and adjustment of the impedance is recorded.

U. S. No. 2,628,315. K. C. Crumrine. Iss. 2/10/53. App. 11/25/49. Assign. The Texas Co.

Subsurface Prospecting. A neutron-gamma logging system using a gamma-ray detector shielded from primary radiation from a radium-beryllium source below it and having a block of heavy water or graphite below the source to reflect downwardly-directed neutrons.

U. S. No. 2,631,270. R. M. Goble. Iss. 3/10/53. App. 5/19/47. Assign. Eastman Oil Well Survey Co.

Method of and Apparatus for the Measurement of Distance or Time Interval by the Use of Compressional Waves in the So-Called Supersonic Range. A system for making a cross-sectional survey of a well and having a supersonic transmitter which rotates and emits a series of wave trains in various azimuths, the wave trains being picked up by a receiver and displayed on a plan-position-indicator at the surface.

U. S. No. 2,631,671. S. Krasnow and L. F. Curtiss. Iss. 3/17/53. App. 5/6/41. Assign. Schlumberger Well Surveying Corp.

Borehole Method and Apparatus. A system for perforating casing and having a radioactivity detector mechanically connected to the perforator so that the casing may be perforated at a location which is accurately known with respect to a radioactive marker.

U. S. No. 2,632,324. L. M. Oberlin. Iss. 3/24/53. App. 12/2/49. Assign. Phillips Petroleum Co.

Apparatus for Determining Permeability. Apparatus for automatically keeping an electrical interface-sensing device at the interface between water and oil while making a permeability test of a well by having the signal from the device control an electrodynamic brake on the windlass.

U. S. No. 2,632,795. F. G. Boucher. Iss. 3/24/53. App. 6/1/51. Assign. Standard Oil Development Co.

Retractable Electrode for Well Casing Measurements. A device for electrically contacting casing in a well by an electrode urged outward by a spring and retracted by a sliding sleeve which rubs against the casing.

U. S. No. 2,632,801. C. A. Donaldson. Iss. 3/24/53. App. 6/5/48.

Deep Well Camera. A pipe-inspecting apparatus for use in a well and having a light beam which circumferentially scans the pipe and is reflected on to a photocell whose output signal is transmitted to the surface and indicated on a c-r tube whose horizontal sweep is synchronized with the scanning.

U. S. No. 2,633,016. J. W. Millington. Iss. 3/31/53. App. 8/29/47. Assign. Sun Oil Co.

Apparatus for Measuring Viscosity. Apparatus for measuring viscosity of fluid in a borehole having a transducer driving a piston in the fluid and connected to an impedance bridge whose unbalance is indicated.

U. S. No. 2,633,484. C. W. Zimmerman. Iss. 3/31/53. App. 7/30/51. Assign. Socony-Vacuum Oil Co., Inc.

Calibration of Logging Systems. A system for calibrating an electromagnetic logging apparatus by coupling to the sonde coil a circuit element having predominantly the characteristic being logged and observing the change in indication, a control circuit being provided to permit selectively coupling either a resistor or condenser.

U. S. No. 2,633,485. H. W. Patnode. Iss. 3/31/53. App. 3/20/52. Assign. Gulf Research & Development Co.

Electrical Dip Meter for Logging Boreholes. A three-electrode electrical dip meter in which each electrode consists of a series of vertically-spaced insulated electrodes, one of which is selected by a contactor which floats on mercury in tubes connected to a common reservoir so that the electrodes being used for the electrical measurement are selected to lie on a horizontal surface which is not influenced by deviation of the borehole.

MISCELLANEOUS

U. S. No. 2,633,015. W. L. Morris. Iss. 3/31/53. App. 10/11/48. Assign. Phillips Petroleum Co.

Portable Permeameter. A permeability testing device in which the time is automatically measured for the pressure in a supply tank to fall from one value to a lower value due to escape of fluid through the core sample.

U. S. No. 2,633,018. R. L. McIlvaine. Iss. 3/31/53. App. 6/11/48. Assign. Herbert Simpson Corp.

Apparatus for Measuring Moisture. A device for determining the moisture content of a standard sample of unconsolidated material and having a postal scale with inverted indicating scale and a heating element above the pan to warm the sample and evaporate the moisture.

SELECTED LIST OF U. S. PATENTS ISSUED DURING THE FIRST QUARTER OF 1953

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* A key to the subject classification system will be found in *Geophysics*, Vol. 12, pp. 256–264 (April, 1947).

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Advances in Geophysics, edited by H. E. Landsberg, Academic Press Inc., New York (1952) Vol. 1, 362 pp.

The connotation in the word geophysics in the title applies primarily to the pure rather than the applied aspects of this science. Consequently, of the eight articles comprising this volume, only two are of direct interest to exploration geophysicists and two others should have considerable application. A fifty-page article on "Aeromagnetic Surveying" by James R. Balsley of the U. S. Geological Survey, and a thirty-page article on gravity and geodesy by George Prior Woollard of the University of Wisconsin belong in the first category. A paper (44 pages) entitled "Automatic Processing of Geophysical Data" by John C. Bellamy of the Cook Research Laboratories, and one (31 pages)

entitled "Some New Statistical Techniques in Geophysics" by Arnold Court of the University of California, Berkeley, Statistical Laboratory, are of more universal appeal, but can be of value to exploration geophysicists. The remaining articles concern themselves with meteorology, estuarine hydrography, and upper atmosphere physics.

The article on "Aeromagnetic Surveying" should serve as an excellent means for introducing this subject to the uninitiated. Included are several appropriate aeromagnetic maps illustrating methods for presenting the data, with emphasis on mineral rather than oil prospecting, as well as related geologic maps. It is unfortunate that the aeromagnetic and geologic maps are not drawn to the same scale, thus precluding the possibility of ready reference for comparative purposes. This is a fault that is all too common in publications in which geophysical and geological maps are included. A Northern Hemisphere map showing aeromagnetic surveys available as of July 1, 1951 to the public either in published or unpublished form, as well as commercially, is an important adjunct to the general information on this subject which is presented in the paper. An excellent bibliography of eighty-nine references dealing with the instrumentation, interpretation, and academic aspects of this relatively new method of magnetic prospecting is one of the major contributions of this article. The maps that are present have been published, for the most part, in one form or another in various journals.

The article by Woollard entitled "The Earth's Gravitational Field and Its Exploitation" serves primarily as a brief introduction and summary, including historical aspects, of the development of our knowledge of the earth's gravitational field and its application to geodesy and gravity prospecting. The sections describing the world-wide network of gravity meter bases and summarizing recent gravity work at sea should be of particular interest to those who have not had the opportunity to familiarize themselves with these advances in the fields of gravity and geodesy. In addition, an appendix listing the comparative gravity values at principal bases throughout the world serves to make this information available in more readily accessible form.

The papers on "Automatic Processing of Geophysical Data" and "Statistical Techniques in Geophysics" should be read by all exploration geophysicists who wish to keep up with the more promising recent developments in their profession. It is inevitable that the techniques and methods discussed in these papers must be applied to exploration geophysical problems in an ever increasing degree if any significant progress is to be made in the processing, as well as interpretation, of the tremendous amount of geophysical data that is becoming available. However, Bellamy has summarized succinctly the present limitation of this approach as follows:

"The greatest shortcoming is the inability of the automatic equipment to produce output records which are capable of convenient and efficient mental assimilation and interpretation."

It is interesting to note that the editor of this volume states that the reason why such fields of geophysics as Hydrology, Seismology, Volcanology, and Tectonophysics were not included in this volume was not because of the absence of advances, but that "considerations of space set a limit to the present effort" (363 pages). It is to be hoped that the emphasis in the next volume will be placed on developments in these fields where, undoubtedly, advances have been made at least of the same order of magnitude as for most of the fields reported in this volume.

RICHARD A. GEYER

Problèmes de géomagnetisme; conférences-rapports présentées au Congrès de l'Association Française pour l'Avancement des Sciences, tenu à Genève du 12 au 16 juillet 1948 (Problems of geomagnetism; lecture-reports presented at the meeting of the French Association for the Advancement of Science held at Geneva, July 12–16, 1948), edited by Alexandre Dauvillier. Paris, Éditions de la Revue d'Optique théorique et instrumentale (1950) 114 pp.

The editor of this volume, as president of the section of geophysics at the sixty-seventh meeting of the French Association for the Advancement of Science, organized this series of reports with the intention of emphasizing important phases of geomagnetism in rapid development at the present time. The five reports are:

(1) Géomagnétisme et géologie (Geomagnetism and geology), by J.-P. Rothé, pages 9–46.
(2) Géomagnétisme dans le passé (Geomagnetism in the past), by Emile Thellier, pages 47–64.
(3) L'état de nos connaissances sur l'ionosphère et ses relations avec le magnétisme terrestre (The status of our knowledge of the ionosphere and its relations to terrestrial magnetism), by Raymond Jouaust, pages 65–76.
(4) Magnétisme terrestre et rayons cosmiques (Terrestrial magnetism and cosmic rays), by Alexandre Dauvillier, pages 77–91.
(5) L'origine du magnétisme terrestre (The origin of terrestrial magnetism), by Alexandre Dauvillier, pages 93–112.

I shall comment briefly on the two reports more closely related to prospecting geophysics. The report by Rothé on geomagnetism and geology is a brief account of the use of the magnetic method to study regional and local geology. It is fairly non-technical with little attention devoted to theory or instruments. However, by the use of maps of actual surveys, mostly European, it emphasizes the use and importance of the method to geologists and mining or petroleum engineers. The author has introduced a distinct novelty for this type of survey article by including an account of the relation of earthquakes to the changes in magnetic anomalies discovered by resurveying, usually after some decades. As examples, maps showing magnetic changes in Japan and the Paris basin are presented and the changes are interpreted as being caused by the movements of magma which are also responsible for known seismic shocks. This section of the report will doubtless also interest those already familiar with the magnetic method.

The report by Thellier on geomagnetism in the past deals with the problem of finding what the geomagnetic field was in past ages through the use of "fossil" magnetism. There are two possibilities being currently studied. The first is fossil thermo-remanent magnetism, produced and preserved in materials like volcanic rocks and artificial baked clays, such as bricks and pottery, which have cooled down through the Curie point at some past time. The second is fossil sedimentary magnetism, exhibited in argillaceous deposits which have been formed by the slow fall of fine particles, some of which were feebly magnetic and were subject to the orientative force of the magnetic field existing at the time of deposit. The problem is complex for it involves not only the physicist but also the geologist or archaeologist, for the fossil magnetic specimens are valueless unless they can be dated.

In connection with the first method, the use of fossil thermo-remanent magnetism, Thellier states that the magnetic properties of volcanic rocks are usually too unstable to be useful and are moreover often affected in their cooled state by lightning or even by the present magnetic field. However, experimental work has shown that artificial baked clays can be used to deduce the inclination and the intensity of the geomagnetic field at the time of manufacture. The declination can not be deduced because the orientation of the brick or vase when fired is ordinarily unknown whereas, as regard the inclination, the firing position of a brick can usually be assumed horizontal, of a vase vertical. Thellier states that measurements on two French samples, one dated in the Gallo-Roman period, the other in the middle of the fifteenth century, showed that the magnetic intensity at Paris has decreased from 0.70 gauss to 0.56 and today to 0.46 gauss, while the inclination values have remained nearly the same. The decrease in intensity agrees with indications already at hand, from analyses of magnetic data of the last hundred years, that a general demagnetization of the earth may be taking place, a possibility of obvious interest for any theory attempting to explain the earth's magnetism.

The second method, the use of fossil sedimentary magnetism, when applied to varves yields data as to the declination, for experimental work has shown that the magnetic moments of the falling particles are dispersed symmetrically with respect to the magnetic meridian. Thus the two methods are complementary. Work at the Carnegie Institution has shown that declination variations have not been greater than those observed during the last four hundred years. More recently M. A. Tuve, as a result of experiments in deducing the magnetic intensity from varves, has announced that the earth's magnetism has probably not varied to any considerable extent in past times.

Thellier gives many details of the work of himself and other French investigators in this interesting report. He remarks at the end of his survey that the American school will in the future dom-

inate all the others because of the material resources which it has available for its work.

This short volume can obviously be recommended to those who read French and wish brief orientations in the fields concerned.

THOMAS A. ELKINS

"Turbidity Currents and Submarine Slumps, and the 1929 Grand Banks Earthquake," by Bruce C. Heezen and Maurice Ewing, *American Journal of Science*, Vol. 250 (Dec. 1952) pp. 849–873.

"Estimated Size of the Grand Banks Turbidity Current," by Ph. H. Kuenen, *American Journal of Science*, Vol. 250 (Dec. 1952), pp. 874–884.

It is not often that an important geophysical hypothesis which has been developing for some time receives a clear and simple confirmation such as is given in the first of these papers. The idea that turbidity currents are important in submarine erosion and deposition has been developing for a number of years. By accident, the Grand Banks earthquake, south of Newfoundland, in November 1929, provided an experiment on a grand scale which has now been interpreted with unusual clarity in terms of turbidity currents. The data have been available for a long time, but the simple interpretation has been developed only recently.

The Newfoundland earthquake was on the steep continental slope and in an area crossed by many submarine cables. Breaks in the cables caused by the earthquake were timed accurately by the recording instruments connected to the cables and their locations were determined by resistance measurements. Several cables on the continental slope and close to the epicenter broke almost simultaneously at the time of the initial shock of the earthquake. Cables down the continental slope and out onto the deep ocean floor broke in a regular sequence at times from 14 minutes to 13 hours after the shock and over a range of distances to 350 km from the epicentral area. The velocity of the impulse causing the breaks, as determined from these times and distances, varied from 55 to 12 knots, with the velocities decreasing regularly with the decrease in slope of the ocean floor. No breaks occurred in any portions of cable on the flat continental shelf.

These facts are now explained as due to an enormous turbidity current initiated by the earthquake and which flowed in a great wave down the continental slope and out onto the ocean floor, with this wave breaking the cables as it passed. In some cases, there was more than one break and sections of cable of as much as 100 miles long were completely lost, apparently either buried in the mud or swept so far away that they were not found.

The second paper attempts to estimate the volume of material involved in the turbidity current and also discusses the mechanics of its formation and movement. The concept is presented that thixotropy plays an important part. It is proposed that a large mass of mud on the continental slope containing on the order of 60 percent water had enough thixotropic strength to hold it in position on the continental slope. The motion from the earthquake is assumed to have destroyed the thixotropic strength practically instantaneously, thus converting this large mass of gelatinous mud into a liquid which then formed a turbidity current without requiring the admixture of additional water. Thus, the phenomenon is in the nature of the flow of a heavy liquid along the sea bottom under the normal sea water rather than in the nature of a landslide. This would explain the high velocity, the very great extent of the flow, and its persistence out over the ocean floor where the slope of the bottom is very low.

The explanation of the breaking of the submarine cables has received a great deal of publicity recently and also has become well known through Ewing's recent Distinguished Lecture tour. These papers give much of the original data from which the turbidity current explanation was derived, as well as reviews of the earlier discussions and proposals for explanation of the cable breaks. They will be of interest to anyone who wishes to look into some of the details involved in this experiment by nature on a grand scale and its simple and straightforward explanation.

L. L. NETTLETON
Gravity Meter Exploration Company

"The Geologic Significance of Seismic Data in the Golden Lane-Poza Rica Area," by D. W. Rockwell, *Bull. Mex. Assoc. of Petr. Geol.*, Vol. 4, Nos. 7–8 (July, 1952) pp. 283–296.

Author's Abstract

A regional map is presented which shows the southern extension of the Golden Lane found by seismic methods. Various geologic cross sections based on seismic data are included which show the reef structure and the relation between the surface layers and the underlying ones. The interpretive technique for the province is discussed. A number of possible applications of existing seismic data to geologic problems are suggested.

The Golden Lane of Mexico is remarkable for being one of the largest oil fields in existence and possibly the richest, in proportion to area and number of wells, in the entire New World. It consists of an enormous buried barrier reef comparable to the great barrier reef of Australia, or to the ancient reef of El Capitan in west Texas. Mr. Rockwell has written a comprehensive and informative summary of the relation of seismic data to the geology of the reef and its surrounding beds, and shown by maps and cross sections how the seismic horizons are distorted, truncated, and bowed over the reef itself. The paper might well serve as a textbook example of what actually happens when reef areas are prospected with the seismograph.

In spite of being such a conspicuous geologic anomaly, the Golden Lane was known as an oil field for years before its true nature as a reef was understood. Indeed, this understanding appears to have been gained only after similar understanding was gained about reefs elsewhere in the oil industry. However, in the past four or five years much seismic work has been done around the Golden Lane, and it has become possible to combine seismic and subsurface data to form a fairly complete overall picture of this remarkable field. A map of the entire region is provided, showing seismograph contours on the top of the Tamabra-El Abra formation (lower Cretaceous) and on this map the reef shows as a north-south zone of no reflections, flanked by every steep dips. The relation between the reef and the Tertiary and Cretaceous beds on its west flank is shown by two geologic cross sections; these are compared with seismic cross sections which demonstrate clearly how the reflecting horizons dip upwards with the reef and are lost in and over it.

The best reflection in the area is one tentatively identified as the top of the Jurassic. It is persistent in character and strength throughout the whole prospect, and can be jump-correlated over great distances. It tends to persist under the reef, though its arrival times are no doubt distorted by velocity anomalies, and further progress in mapping it is dependent on increased velocity information.

An interesting feature of the reef itself is the existence of several discontinuities formerly thought to be faults but now demonstrated to be ancient channels through the reef comparable to the river channels or lagoon openings through modern reefs. These can be plainly seen in the seismic data.

The part of Mr. Rockwell's paper which makes it unusual to readers of North American geological literature is the number of possibilities suggested for further prospecting and drilling. Since Petroleos Mexicanos has no competitors it is perfectly proper to suggest locations for additional drilling and prospecting, and Mr. Rockwell takes an optimistic view of the oil possibilities in the terraces at the foot of the reef, in the line of noses northeast of the reef, in small anomalies which might be called "reefs within reefs" and ought to produce if they are properly capped by impervious layers, in stratigraphic traps in the Chicontepec and in other unexplored seismic structures in the neighborhood.

In conclusion there is a discussion of the geologic history of the area, coupled with a suggested explanation for the production low on the east flank and a prediction that certain seismic structures now uninteresting because of lack of closure may well constitute oil traps. In this connection it would be interesting to discuss the application of Hubbert's fluid drive theory with the author.

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Houston

"Seismic Refraction Shooting in an Area of the Eastern Atlantic," by M. N. Hill, Phil. Trans. Roy. Soc. Lon., Ser. A., No. 890, Vol. 244 (1952) pp. 561–596.

This is the first complete report of British seismic work in deep water. The technique differs from that developed by the Columbia University group under Ewing in that a single ship is used for shooting and recording. Four FM sono-radio buoys relay the seismic waves detected by a crystal hydrophone suspended below each buoy at a depth of about 150 feet.

The experiments were carried out at three positions in the eastern Atlantic around the point 53°50'N, 18°40'W, where the water depth is approximately 1,300 fathoms. Topographically the area appears to be at the foot of the continental slope in an embayment between Rockall bank and the British Islands. The results showed an uncrystalline sedimentary layer in which the velocity of compressional waves increased from the value for sea water (4,900 ft/sec) at the surface to a limiting value of 8,200 ft/sec, the gradient having an approximate value of 2.5/sec. Thickness of this layer varied from 6,200 ft to 9,700 ft. Below the sediment was crystalline rock, with compressional wave velocity of approximately 16,500 ft/sec and thickness varying between 8,800 ft and 11,100 ft. The lowest layer indicated gave a value of about 20,500 ft/sec for the compressional wave velocity with thickness undetermined.

Similar investigations by Ewing and his co-workers in corresponding areas off the east coast of North America also indicated the presence of unconsolidated and semi-consolidated sediments lying on crystalline basement having a compressional velocity range of 15,000–18,000 ft/sec. Below this is an intermediate layer with velocity about 22,500 ft/sec. The Mohorovičić discontinuity was located at a depth of about 10 miles. In these respects the results of both groups are comparable.

It should be emphasized that these measurements were made in the zone of transition between continental and oceanic structures. One would not expect results comparable to those reported for the ocean basin proper where the low velocity basement layer is absent and the Mohorovičić discontinuity occurs at a depth of about 6 miles below sea level.

Hill offers a new interpretation of low-frequency arrivals following the direct sound through the water. He suggests that they represent single and multiple refractions through a sediment having a linear gradient of velocity. It is curious that multiple reflections from the sea bottom were not observed. These arrivals are prominent features on most deep sea seismograms obtained by the Columbia University group. It is possible that this difference is mainly instrumental since multiple bottom reflections often occur with frequencies above the 200 cps limit of Hill's gear.

FRANK PRESS
Lamont Geological Observatory
(Columbia University)

Rayleigh Wave Coupling to Atmospheric Compression, by W. S. Jardetzky and Frank Press, *Bull. Seis. Soc. Am.*, Vol. 42, No. 2 (April, 1952) pp. 135–145.

The period equation of Rayleigh waves is derived for the following three-layer situation: a semi-infinite fluid overlying a solid elastic stratum over a semi-infinite elastic solid. This period equation consists of a member which is identical to the period equation for the case of a free surface plus correction terms due to the presence of the fluid. If this fluid is taken to be air, the density is in most practical cases three orders of magnitude less than that of the solid stratum and the correction terms are negligible except in the vicinity of the frequency for which the phase velocity of the free surface case is equal to the speed of sound in air. By analogy with previously calculated cases (Press and Ewing) for which the surface layer was considered as a liquid, it is to be expected that an air-coupled Rayleigh wave will exist in the vicinity of this frequency. In order that this air-coupled Rayleigh wave exist, the speed of sound in air must exceed the Rayleigh wave velocity in a semi-infinite elastic solid having the same elastic properties as the surface stratum.

IVAN TOLSTOY

Two Slow Surface Waves Across North America, by Frank Press and Maurice Ewing, ***Bull. Seis. Soc. Am.***, Vol. 42, No. 3 (July, 1952), pp. 219–229.

It is shown that in many instances Love waves having a purely continental path are characterized by reversed dispersion and very little attenuation. Furthermore, the range of observed group velocities is so great that the duration of the dispersive wave train on a seismogram is an order of magnitude greater than that expected from the ordinary theory of Love waves for continental areas. It is suggested that this feature could be explained by assuming that the sialic crust (limited to continental areas) is underlain by an incompetent material which does not transmit shear very well. In such a case, the dispersion curves would approximate the well known classical curves for a perfect wave guide. This paper provides an excellent illustration of the valuable ideas which may be reached through an understanding of the dispersive properties of elastic surface waves.

IVAN TOLSTOY

"Rilievo gravimetrico della Sicilia" (Gravity survey of Sicily), by E. Medi and C. Morelli. ***Annali di geofisca***, Vol. 5, No. 2 (April, 1952) pp. 209–245.

This survey consists of 299 stations made with two Worden gravimeters during the period February 28–May 16, 1952. The observed values were tied to the Potsdam absolute system. The greater part of the paper is made up of tables giving descriptions, locations, observed and reduced gravity values for the stations, and details of the adjustments of first and second order gravimeter station networks to which the detail stations were referred. Maps showing the station locations and the gravity contours for the generalized Bouguer anomaly are also presented.

Two reduced gravity values are listed, the Faye anomaly and the generalized Bouguer anomaly. The Faye anomaly is the usual free air anomaly; the generalized Bouguer anomaly includes the spherical cap correction through Hayford's zone O_2 and topographic corrections through zone L.

By way of interpretation of the generalized Bouguer anomaly map it is concluded that the large central negative anomaly represents a depressed area in which laminated clays have accumulated. It is also interesting to note that the lava flows of Mount Etna are scarcely visible in the contours, which is interpreted to mean that the volcano is confined to the outermost crustal layers.

THOMAS A. ELKINS

"Gravity Observations in a Borehole," by R. L. G. Gilbert, ***Nature***, Vol. 170, No. 4323 (September 6, 1952) pp. 424–425.

This is the first report that has come to this reviewer's attention giving the results of successful gravity observations in a borehole. The instrument employs a new principle (the resonant period of a vibrating ligament varies with the tension due to a suspended weight) and has been previously reported by the same author,[1] who has now developed it for borehole use under the auspices of the Anglo-Iranian Oil Company.

These first results are not very accurate. The probable error is ± 0.7 milligal for a single observation or 1.0 milligal in a difference. This reduces to a probable error of ± 0.1 cgs unit in the density computed from the gravity difference observed between the top and bottom of each 400-foot layer. This method of obtaining density has been demonstrated by Hammer[2] using gravimeter measurements in a vertical mine shaft. The Gilbert data were obtained from two round trips in the same borehole making two observations at the same points on each trip. By averaging the gravity differences for each 200-foot interval, after discarding one group of bad values, an apparent accuracy of ± 0.11 cgs unit was obtained.

An unspecified number of cutting samples measuring approximately one millimeter on a side gave wet and dry density values in fair agreement with the computed values and within the apparent range of accuracy for three out of a total of four 200-foot intervals measured. For one 100-foot interval

[1] R. L. G. Gilbert, *Proceedings of the Physical Society*, B, Vol. 62, 445 (1949) London.

[2] Sigmund Hammer, "Density Determinations by Underground Gravity Measurements," *Geophysics*, Vol. 15, 637–652 (1950).

measured at the bottom of each trip the agreement between the sample values and the value computed from the average gravity difference was excellent.

It is to be hoped that more data of this kind will soon be available.

L. H. BAILEY
Gulf Research & Development Company

"Magnetic Exploration for Chromite," by H. E. Hawkes, *U. S. Geol. Survey Bull.* 973-A (1951) pp. 1–21, 15 cents.

This paper is of prime interest to geophysicists interested in the interpretation of magnetic data. The paper summarizes the problem of magnetic exploration for chromite, reviews the published literature on the subject, and presents the results of experimental surveys by the author in 1941 on some of the more important chromite deposits of the western United States.

Mineralogically, chromite is a member of the isometric spinel group, and its chemical formula is commonly written $FeO \cdot Cr_2O_3$. Inasmuch as chromite almost invariably contains magnesia, alumina, and ferric iron in addition to chromium and ferrous iron, the formula might more correctly be written $(Mg, Fe)O \cdot (Cr, Fe, Al)_2O_3$. Complete isomorphism apparently does not exist within the limits of this formula. Compositions of naturally occurring chromites vary from magnetite, $FeO \cdot Fe_2O_3$; to magnesiochromite, $MgO \cdot Cr_2O_3$; and spinel, $MgO \cdot Al_2O_3$; with small proportions of ferrochromite, $FeO \cdot Cr_2O_3$. For simplicity, the composition of chromite may be regarded as varying from magnetite to magnesiochromite and spinel, with some substitution of FeO for MgO. As one of these end members is highly magnetic (magnetite) and the other two essentially nonmagnetic (spinel and magnesiochromite), the magnetic properties of chromite may vary widely.

Undoubtedly the magnetic properties of chromite are related either directly or indirectly to its other chemical and physical properties. It has been found that wherever comparative observations on the various chemical and physical properties of chromite have been made, a rough parallelism exists between increasing iron content and increasing magnetic susceptibility.

H. K. Stephenson found that the highly magnetic chromites from Casper Mountain, Wyoming, show considerably higher magnetic susceptibilities at field strengths of 200 gauss than at 0.3 to 2.6 gauss. This property of chromite is in contrast with the results of experiments by P. Weiss and others which demonstrate that for magnetite the susceptibility measured in a field of a few hundred gauss is generally lower than the susceptibility measured in a field of a few gauss.

Susceptibility determinations on individual chromite specimens can be misleading, owing to the apparent variability in the susceptibility of specimens collected from the same area or even from different parts of the same deposit. Chromite is commonly nonmagnetic or only very weakly magnetic. Only in a few localities is it strongly magnetic.

Geologically, the occurrence of primary chromite is limited to segregation products of ultramafic magmas, and primary chromite is always found lying within the limits of the ultramafic mass. The two distinct varieties of chromite deposit are the "sackform" and the "stratiform" types, terms suggested by the characteristic shape of the deposits. The sackform type, characteristic of the dunites and peridotites of certain geosynclinal belts such as the Coast Range of California, ranges from massive chromite to sparse disseminations of chromite grains in a silicate matrix. The sackform chromite deposits occur in the enclosing ultramafic rocks as clusters, linear zones, or randomly scattered lenticular or irregular bodies, often lacking any perceptible control. The stratiform type, found only in the lower ultramafic layers of differentiated norite or gabbro sills, consists of chromitite layers that commonly maintain a fairly consistent stratigraphic relationship to the primary igneous layering and to the marginal contacts of the sill. Examples are the tabular chromitite bodies of the Stillwater complex in Montana, the Bird River complex in Manitoba, and the Bushveld complex in South Africa.

As chromite is always found lying within the limits of the ultramafic mass, the problem of prospecting for primary chromite is twofold—first, to locate bodies of the ultramafic host rock and, second, to locate the concentrations of chromite within the ultramafic bodies. The ultramafic host rock can usually be distinguished from other common rock types by magnetic methods. Thus, if a

knowledge of the location, contacts, or shape of the ultramafic host rock is helpful in prospecting, magnetic methods can be of indirect help in chromite exploration. The direct detection by magnetic methods of concentrations of chromite ore within the ultramafic mass, although apparently possible in some areas, presupposes a rare combination of circumstances that can be expected only in exceptional cases. The author states that "for the direct detection of chromite it is necessary that the chromite be characteristically magnetic and that the country rock be uniformly nonmagnetic." In most areas described in the literature or examined by the author, magnetic methods showed no promise as a means of direct detection of chromite bodies. Even in areas where "successful" results were reported, the surveys apparently were successful only in that the method showed promise.

The author states that "magnetic methods have been applied to chromite prospecting far more often than would seem to be warranted by its undistinguished magnetic properties." Of at least 30 known areas where magnetic surveys have been made, "the author knows of no discovery of a commercial deposit of primary chromite resulting either directly or indirectly from magnetic-survey work."

Concentrations of chromite in placer deposits have been of commercial interest in at least one locality. Placer chromite commonly occurs in association with other heavy minerals such as magnetitie, garnet, zircon, olivine, gold, and platinum.

Magnetic exploration for placer deposits is an entirely different problem from exploration for primary chromite ore. Placer chromite deposits in beach terraces of the Oregon coast, for example, have been discovered by magnetic methods. These deposits are magnetic by virtue of their magnetite content, which commonly ranges from 1 to 7 percent.

KENNETH L. COOK

"The Distribution of Radioactivity," by R. I. B. Cooper, *Nature*, Vol. 169 (1952) pp. 350–356.

The paper is an account of a geophysical discussion among selected members of the Royal Astronomical Society on recent advances in our knowledge of the distribution of radioactivity in terrestrial rocks and in meteorites. The paper presents the subjects brought forward for discussion and summarizes the comments of the participants. Little detail is given.

Some of the subjects discussed and their conclusions were:

1. Range of variation of the quantity of radio elements in terrestrial rocks and ores.
2. Range of variation of the thorium to uranium ratio in terrestrial rocks and ores. Concluded: Ratios of 4:1 to 10:1 have been observed.
3. Radio element distribution in sediments and in igneous rocks. Concluded: A variation of radio elements within batholiths and the similarity of radioactivity of ocean and continental basalts have been observed.
4. Genesis of ores bearing radio elements, such as pitchblende. Concluded: field evidence indicates a granitic parentage.
5. Radio elements in meteorites. Concluded: New fluorescent techniques have established variations of uranium between various meteorites which may tend to alter previous astronomical theories as to their origin.
6. Sampling methods to obtain representative values for earth materials. Concluded: of present methods, the areal ionization measurements give the best average.
7. Heat flow measurements through the continental areas and through the ocean floors. Concluded: If ocean measurements can be relied upon (members were skeptical) then the measurement indicates that each vertical column of the crust has the same quantity of radio active substance.

More detailed presentations of the last three subjects by the members of the Society will be welcomed.

PAUL WUENSCHEL

"Radioactivity as a Guide to Ore," by W. H. Gross, *Econ. Geol.*, Vol. 47 (1952) pp. 722–742.

The author suggests the use of "higher than normal" natural radioactivity of surface rocks within the confines of a stock or batholith as an indicator of structural deformation within the pluton and possibly as an indicator of ore mineralization. The basic assumption is a theory of ore genesis (not universally accepted) that demands that pegmatite and ore solutions (the former which are highly radioactive) both originate as a residual liquid from the cooling of the same acid or intermediate magma. Structures that localize one also localize the other. He believes that the residual solutions will pass through the mesh of early formed crystals as the solutions move down a pressure gradient caused by structural deformation.

A decreasing pressure gradient may be accompanied by a decreasing temperature gradient which will cause precipitation along the migration path. He then reasons that the "higher than normal" radioactivity should indicate low pressure areas along which ore may occur.

He corroborates the radioactive assay with a determination of zircon, silica, and heavy metals at each station. The zircon distribution should shed light on movement of residual pegmatite solutions; the silica is normally associated with higher than normal, and the heavy metals indicate ore mineralization.

He presents nine examples, two of which are barren of ore, but possessing radioactive highs, two of which have ore but have weak radioactive anomalies, and five examples which show good agreement. Neither zircon nor the heavy metals are consistent in their relation to their radioactive anomalies.

The reader will become disappointed w th this method of prospecting because of the continual need to inject additional hypotheses to explain the many inconsistencies that arise. He may feel that the method has merit but much more data must be gathered and a more reliable sampling procedure developed in order to isolate the many variables.

PAUL WUENSCHEL

"Autoradiographic Study of Marine Shales," by Virginia F. Ross, *Econ. Geol.*, Vol. 47 (1952) pp. 783–793.

The author uses the autoradiographic method of x-ray assaying to determine the locus of radio elements of the uranium and thorium series in marine shales.

She discusses the method of preparing the thin sections, prior to exposure to the photographic emulsion, when the sample is of coarse structure, fine structure of opaque material, and fine structure of transparent material. A researcher anticipating the use of this autoradiographic technique on soft materials will profit by reading this paper. Swedish Kolm, Woodford shale, Cherokee shale, and Miocene nodular shale from California were studied. She concluded that alpha radiation comes from both inorganic and organic constituents and that activity increases with sulfide content.

Although she discusses the method of assaying, she leaves the reader who is not familiar with optical techniques with doubt in his mind as to the assurance with which organic matter can be determined under the microscope and also as to how she rules out the possibility that an alpha track may come from non-radioactive organic matter forming a film after a radioactive inorganic granule of the thin section.

PAUL WUENSCHEL

"On the Natural Radioactivity in the Air," by I. H. Blifford, L. B. Lockhart, Jr., and H. B. Rosenstock, *J. Geophys. Res.*, Vol. 57 (1952) pp. 499–509.

Radon and thoron diffuse from the soil into the atmosphere and there build up along with their respective daughter products. Equilibrium within these series will exist when the rate of decay equals the rate of formation of each isotope. The purpose of the present paper is to determine whether or not this equilibrium exists. The authors determined the amount of each daughter product of radon

by either beta ray assay or chemical analysis. They find that equilibrium does not exist among radon and her daughters and conclude that some process is removing the isotopes from the air. Of the three possible modes of removal, namely, by rain, by attraction to earth because of earth's gravitational field, by attraction to the earth because of its electrical field, the former was found to be the major mode.

PAUL WUENSCHEL

"The Electric Field of a Long Current Carrying Cable on a Stratified Earth," by J. R. Wait, *J. Geophys. Res.*, Vol. 57 (1952) pp. 481–485.

The author extends Evans solution for the axial component of the electric field due to a low frequency alternating current flowing in an infinite horizontal wire lying on the surface of a two layered earth. Displacement currents in the air and in the two layers below the surface of the earth are neglected. The conductivity of the lower layer is taken to be greater than the conductivity of the upper. The solution is presented in tabular form for ease in application.

PAUL WUENSCHEL

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Annali de Geofisica, Vol. 5, No. 4 (October, 1952)
Boletin de la Asociacion Mexicana de Geologos Petroleros, Vol. 4, Nos. 9–10 & 11–12 (Sept.–Oct. & Nov.–Dec., 1952); Vol. 5, Nos. 1–2 & 3–4 (Jan.–Feb. & March–April, 1953)
Bulletin d'Information de l'U.G.G.I., Vol. 2, No. 2 (1953)
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Journal of Geophysical Research, Vol. 58, No. 1 (March, 1953)
Proceedings of the Cambridge Philosophical Society, Vol. 49, Part 2 (April, 1953)
Quarterly Journal of the Geological Society of London, Vol. 108, Part 4 (March 31, 1953)
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Science, Vol. 117, Nos. 3034–3046 (Weekly February 20 through May 15, 1953)
Scientific Monthly, Vol. 76, Nos. 3 & 4 (March & April, 1953)
Tellus, Vol. 4, Nos. 3 & 4 (Aug. & Nov., 1952); Vol. 5, No. 1 (February, 1953)

DISCUSSIONS AND COMMUNICATIONS

NOTE ON THE EFFECT OF RANDOM ERRORS IN GRAVITY SECOND DERIVATIVE VALUES*

G. RAMASWAMY†

In an interesting paper "The Effect of Random Errors in Gravity Data on Second Derivative Values," Thomas A. Elkins (1952) points out the need for eliminating the random component of gravity data before proceeding to interpret them with the aid of second derivative maps. There is a *prima facie* case for the elimination of random errors, if only to ensure reliability in results. The need, however, becomes more apparent if it is remembered:

a. that the Second Derivative method of interpreting gravity (or magnetic) data is one of high resolving power, and
b. that, therefore, errors creeping into those data may considerably vitiate the interpretation of those data.

Briefly stated, the method employed by Elkins for this purpose is as follows:

A set of 111 balls of specified shape (known as "pills") is marked with error values which follow the well known Gaussian Normal Distribution with probable error 10. These balls are put into a container, mixed thoroughly and are removed one by one. The observer replaces each of them after noting down their values as many times as there are entries in the gravity data grid. A "Random Error Grid" is thus prepared, for which second derivative values are computed and contoured. Finally, qualitative comparison is made of the second derivative map computed from the field data and that from the error grid. Anomalies are evaluated on this basis.

The author of this note is of the opinion that Elkins' method for preparing the "Random Error Grid" has certain defects and it is not always to be recommended. It is the aim of this paper to point out the shortcomings inherent in Elkins' method and to suggest an alternative procedure which should avoid them.

It is known (Tintner, 1952) that the random component of a time series under very general conditions (which need not detain us here) follows the Gaussian Normal Distribution of errors:

$$p(x)dx = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-M)^2}{2\sigma^2}\right) dx, \tag{1}$$

where $p(x)dx$ is the probability of the error variable falling in the interval $(x, x+dx)$, and M and σ are parameters of the distribution function, known as the "mean" and "Standard Deviation" of the distribution, respectively. In the case of our field data, the mean may be taken to fluctuate around zero and hence:

$$M = 0. \tag{2}$$

The Standard Deviation of the error is not known and has to be estimated. It follows that we have only to get a random sample of size equal to the number of values on the gravity data grid from a normal population having zero mean and a suitably chosen Standard Deviation.

For this purpose Elkins draws the balls from a container and takes down the values on them. This method is on the face of it both tedious and cumbersome, especially when a series of grids is to be screened for error. Furthermore, the worthiness of the container and the uniformity of the balls must be "tested" beforehand. The difficulty of "Artificial Sampling Experimentation" (included

* Manuscript received by the Editor November 30, 1952.
† c/o T. T. Conger, Standard-Vacuum Oil Company, Calcutta, India.

in Elkins' procedure) has been pointed out by Karl Pearson in a different context. He states, "In the case of many problems we may both check theory and prevent the pure algebraist, as he is apt to do, outrunning statistical experience by an appeal to the test of artificial sampling. Even when we are dealing with small samples—since, we have as a rule to take a large number of them—the work of testing is very laborious. It is complicated by the fact that drawing balls or tickets from a bag or urn, however pleasing in theory to the mathematician, transcends the powers of practical statistician. . . . Practical experiment has demonstrated that it is impossible to mix the balls or shuffle the tickets between each draw adequately . . . in short, tickets and cards, balls and beads fail in large scale random sampling tests." (Pearson, 1927)

Another disadvantage in Elkins' method is that every time a set of error values on the balls has been noted down, it is to be tested for its "randomness," applying what is known as the "χ^2—Test" on the set. It is, however, to be noted that the computation of χ^2 for a large number of values will in itself take time. Surely, geophysicists would like to have a method devised to avoid this. Again, if one set of error values is found to be not random in the statistical sense, the operation of drawing balls is to be repeated again and again until the "χ^2—Test" ensures the randomness of the set. This is a striking weakness in Elkins' method, and it ought to be avoided. In Elkins' method the error values are rounded out and very many probable error values are not marked on the balls. Thus, in Elkins' experiment (described in his paper) values like 25, 29, 31, 36, 37, and 38 are not marked, while values like 26, 30, 40 are marked. This probably explains why a set of random error values prepared according to Elkins sometimes fails to be "random." Thus, Elkins' method amounts to drawing a finite sample from an infinite population, which, in turn, is generated from a finite number of values.

It will now be apparent that Elkins' method fails in some important and desirable aspects. In order to get over the difficulty of "Artificial Sampling Experimentation," Tippett (in Pearson, 1947) prepared a table of random numbers ranging from 0000 to 9999, using census reports. Subsequently P. C. Mahalanobis and his associates (1934) of the Indian Statistical Institute converted the whole set of 10,400 random deviates from a normal population with mean value zero and Standard Deviation equal to unity. If a sample of size n from a normal population $N(M, \sigma)$, with mean M and Standard Deviation σ is required, the tables prepared by Mahalanobis and his associates may be referred to and n values of $X_i (i = 1, 2, \ldots n)$ taken from them, in any order; the formula

$$X_i = M + x_i\sigma \tag{3}$$

may then be used to find the corresponding values of X, which are desired.

The following are certain features of the tables computed by Mahalanobis and his associates:

1. After heavy computational labor, the actual frequency constants for the whole sample of 10,400 were calculated. Comparing these with the expected values of the constants, it was concluded that the difference between observed and expected values of the frequency constants is statistically insignificant in every case.

2. The sample of 10,400 values may be considered as a whole to be a truly random sample from a normal population, at least up to the sixth moment.

3. The normality of the sample was variously tested by testing the distribution of χ^2 and of mean and Standard Deviation of the sample and also by applying the "χ^2—Test" for each of the 104 samples of size 100 out of the whole set of 10,400 values.

4. The "χ^2—Test" has already been applied and the experimenter need not do it again for himself.

It should now be apparent to the reader that the alternative procedure above is preferable, as it ensures quicker and more reliable results. To keep this note within limits, illustrations of this alternative procedure are not given here; it is hoped that the reader will have no difficulty in preparing one for himself and to draw conclusions therefrom.

The author is at present working out on a "General Theory" to attack the problem presented by Elkins, who has clearly brought to light the dangers in interpreting the second derivative maps without checking the accuracy of the underlying field data. The author hopes to publish this theory shortly.

The author wishes to thank Mr. Matthew T. Murray of the Standard-Vacuum Oil Company, Calcutta for his help and encouragement.

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POKING FUN AT "OUR HUMAN ASSETS"

To introduce his presidential address, "Our Human Assets in Geophysics" (printed in this issue of *Geophysics*) at the Houston meeting, retiring President Curtis Johnson displayed these cartoons from colored slides with the following comments:

"In considering our human assets in geophysics we quickly recognize that one of our most important assets is the fine cooperation existing between geologists and geophysicists. No one will deny that this cooperation and mutual understanding did not always exist. It may be interesting, therefore, to look back at the manner in which geophysicists were once viewed by geologists, and vice-versa.

"When geophysics first appeared on the exploration horizon, geologists were inclined to think of the geophysicist as a 'doodlebugger'—a willow-wand crack-pot (Figure 1).

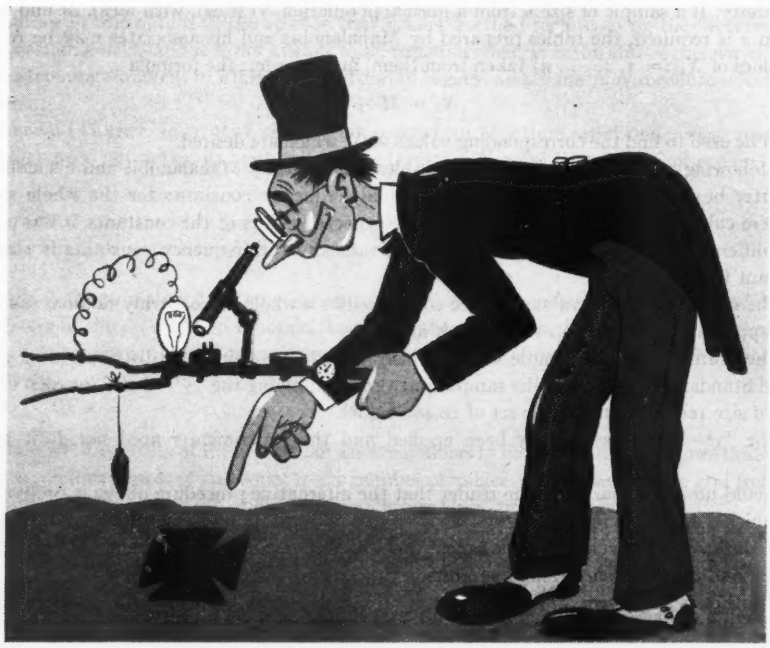


FIG. 1. The Doodlebugger.

FIG. 2. The Dynamite Kid.

FIG. 3. Seismo the Great.

FIG. 4. The Complacent Geologist.

"They soon had to revise their opinion, however, as activity in geophysics increased. So great was the activity, in fact, that the new conception of the geophysicist became the 'Dynamite Kid' (Figure 2). People, houses, even cows and chickens existed precariously in the vicinity of this activity.

"The geologist was slow to revise his opinion, but eventually he had to admit that geophysics had become highly scientific—in fact it partook at times of magic (Figure 3). The pendulum had swung too far the other way. 'Seismo the Great' could apparently pull oil wells from his hat.

"Meantime, of course, the geophysicist had his early ideas of the geologist. Out of deference to our esteemed colleagues we present only one such picture (Figure 4) of a withered old tycoon, past his prime but resting complacently on his laurels under the crest of 'geologist's picks rampant.' "

In forwarding the cartoons to the Editor, Johnson writes, "The ideas for the cartoons originated over a couple of beers shared by the author and Don Sweeney, an unprincipled member of General Petroleum's Public Relations Staff. The ideas were embellished and the cartoons drawn by Bill Fox, Editor of *Doings in General*, the monthly employee magazine of General Petroleum. I would like to express my appreciation to these co-plotters and to the members of the Houston audience who received the cartoons so generously."

CURTIS H. JOHNSON

CONTRIBUTORS

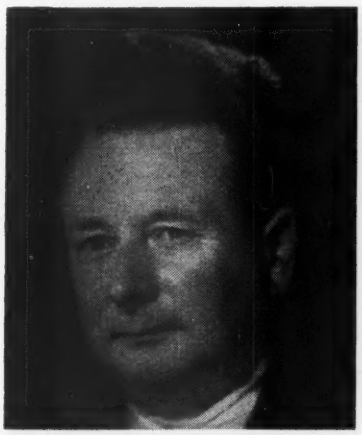
DAVID F. BLEIL

DAVID F. BLEIL, a native of Michigan, received B.S. degrees in Engineering Mathematics and Engineering Physics in 1934, and an M.S. degree in Mathematics in 1937, from the University of Michigan. His Ph.D. degree was conferred by Michigan State College in 1948.

He taught and conducted research in the Physics Department of Michigan State College from 1936 until he joined the staff of the Naval Ordnance Laboratory in 1943. While at NOL during World War II he worked with the Electricity and Magnetism Division. There he became interested in an investigation of a project on induced polarization as a method of geophysical prospecting. As a result of this work he was made a consultant to the U. S. Geological Survey. The same project served as the basis of Dr. Bleil's dissertation and was cited in a report to the President in "Resources for Freedom, Vol. IV, June 1952," which was made by the President's Materials Policy Commision.

Dr. Bleil is at present Deputy Chief of the Physics Research Department of the Naval Ordnance Laboratory, and combines with his administrative duties research in the fields of anti-ferromagnetism and magnetostriction. He is also a member of the ONR Solid State Advisory Panel charged with surveying work in this field done under ONR.

Professional memberships include the Society of Exploration Geophysicists, the American Physical Society, the Philosophical Society of Washington, Sigma Pi Sigma and Sigma Xi.



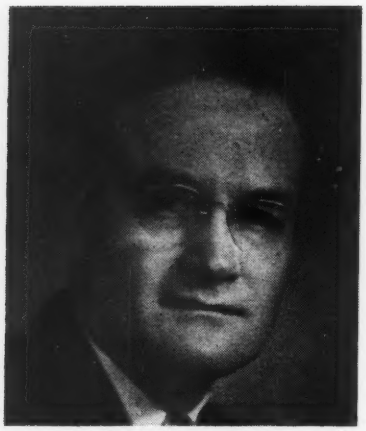
LOUIS CAGNIARD

LOUIS CAGNIARD, graduated from the École Normale Supérieure, "Agrégé" of Physics in 1924, made his scientific debut as assistant of the late physicist G. Bruhat.

After having received his Doctorate in physics (1928), he was appointed director of the Societé de Prospection Géophysique, a concern specializing in gravimetric and magnetic research work, which later, in 1936, united with the Compagnie Generale de Géophysique.

He received his Doctorate in mathematics in 1938, and put aside for a while his activity in practical prospecting problems in order to teach Physics of the Earth in the Science Faculty of the Strasbourg University.

Since 1946, he has been teaching Applied Geophysics in the Faculty of Science at Paris.



CECIL H. GREEN

CECIL H. GREEN was born in England but was brought to Canada at an early age and obtained his grammar and high school education in Vancouver, British Columbia. He attended the University of British Columbia for undergraduate work and received his S.B. and S.M. degrees in Electrical Engineering in 1924 from the Massachusetts Institute of Technology.

Until 1926 Mr. Green was a development engineer in the A. C. Engineering Department of the General Electric Company at Schenectady, New York. During this period, he also served as an instructor in advanced engineering classes. He then turned to the newer field of electronics and became research engineer for Raytheon Manufacturing Company. In 1928 he became development engineer for Federal Telegraph Company, where he was in charge of the radio transmitting tube department of the Newark, New Jersey, plant.

In October 1930 Mr. Green joined the newly organized Geophysical Service Inc. After serving as party chief in Oklahoma, Texas and Louisiana, he became a supervisor in 1936 with headquarters in Shreveport, Louisiana. Subsequent headquarters were at Midland, Texas, and Bakersfield and Los Angeles, California. During this period he also handled special assignments in Ecuador, Venezuela, Western Canada, Egypt, Iraq, Saudi Arabia, India and Sumatra.

In 1941 he was promoted to vice president in charge of operations and in 1950 became president of Geophysical Service Inc. He also serves as an executive of various GSI affiliate companies.

Mr. Green is a past officer in several capacities of the Society of Exploration Geophysicists: Secretary-Treasurer 1945–46; Vice President 1946–47; and President 1947–48. He has served as chairman of the SEG Honors and Awards Committee and is at present a member of the Constitution and By-Laws Committee, Publications Committee, and the Joint AAPG-SEG-SEPM Advisory Committee on Radioactive Mineral Exploration. He is a member of the American Association of Petroleum Geologists (National Committee on Applications of Geology 1944–45), Society of Exploration Geophysicists, American Geophysical Union, Mexican Association of Petroleum Geologists, European Association of Exploration Geophysicists, Society of Exploration Geophysicists of Japan, American Society for Engineering Education, Society for the Advancement of Management, American Institute of Management, Dallas Geological Society, and Dallas Geophysical Society.

PATRICK A. HEELAN

PATRICK A. HEELAN, S.J., was born in Dublin, Ireland, in 1926. He entered the Society of Jesus in 1942. He subsequently studied pure and applied mathematics at University College, Dublin, and received his B.A. and M.A. degrees with honors there. From 1949 to 1951, he held a Travelling Studentship from the National University of Ireland, under whose auspices he studied geophysics at Saint Louis University. He received his Ph.D. in 1952 from this institution, majoring in geophysics with a minor in mathematics. He was employed for a while as Lecturer in Geophysics at Saint Louis University. Since the summer of 1952, he has been resident at Saint Stanislaus College, Tullamore, Ireland. He is a member of Sigma Xi, the Seismological Society of America and the Society of Exploration Geophysicists.

RICHARD N. JOLLY

RICHARD N. JOLLY received the B.A. degree in Physics from the University of Texas in 1940. He was employed by the Carter Oil Company subsequent to graduation and served in various capacities on domestic gravity and seismic crews. In late 1941 he was transferred to the Netherlands East Indies as seismograph operator. This assignment was terminated by the outbreak of war, and in 1942 he was granted a leave of absence to enter the Air Force.

Upon completion of training in meteorology at the University of Chicago, Mr. Jolly was commissioned and sent to the China-India-Burma Theater, where he served as a weather officer for two years, attaining the rank of Captain.

Mr. Jolly returned to Carter in 1946 and spent a year as operator on an experimental seismic crew. He was subsequently transferred to the Carter Research Laboratory as a research physicist, in which capacity he is now employed.

Mr. Jolly is a member of Phi Beta Kappa, the Society of Exploration Geophysicists, and the Geophysical Society of Tulsa.

H. W. MARCH

H. W. MARCH was born at Ocheyedan, Iowa, December 14, 1878. He received the A.B. and A.M. degrees at the University of Michigan in 1904 and 1905, respectively, and the Ph.D. degree in theoretical physics at the University of Munich in 1911. He was an assistant in astronomy at Michigan from 1902 to 1905, an instructor in physics at Princeton for the year 1905–06 and an instructor in mathematics at Wisconsin from 1906 to 1909. After two years of study in Germany he returned to Wisconsin in 1911 and was successively assistant professor, associate professor, and professor of mathematics until his retirement as professor emeritus in 1949. From 1928 to 1951 he was a consulting mathematician at the U. S. Forest Products Laboratory in Madison, Wis. For five years, 1941–46, he was on leave from the University for full time work at the Laboratory. At the Laboratory he was the author of many reports on the elastic behavior of wood as an orthotropic material and on design criteria for laminates, in particular plywood and sandwich, in aircraft construction.

A biography and photograph of HENRY C. CORTES appeared in *Geophysics* in 1945 (Vol. 10, pp. 124–25). Since that time he has been promoted to the position of Assistant Manager Exploration Department, Magnolia Petroleum Company, Dallas. In addition, he has held since 1945 the following offices and committee assignments: Society of Exploration Geophysicists: President, 1945–46, Chairman, Committee for Geophysical Case Histories, Volume I, 1946–48; Dallas Geological Society: President, 1945–46; American Association of Petroleum Geologists: Trustee of Research Fund, 1949–51 (Chairman of Trustees, 1951), Medal Award Committee, 1945–46; Committee on Applications of Geology, 1941–44 (Vice-chairman for Geophysics), Business Committee, 1950–51. Dallas Petroleum Club: President, 1953–54.

At present he is a member of the following organizations: Petroleum Engineers Club (Dallas). Dallas Petroleum Club, Petroleum Club of Houston, The American Association of Petroleum Geologists, Society of Exploration Geophysicists (Charter Member), Dallas Geophysical Society, American Geophysical Union, Texas Academy of Science (Sustaining Member & Fellow), American Association for the Advancement of Science, National Oil Scouts & Landmen's Association, Engineers Club of Dallas, Mid-Continent Oil & Gas Association, and the Eastern Section of the Seismological Society of America.

ENDERS A. ROBINSON

ENDERS A. ROBINSON received a S.B. degree in Mathematics in 1950 and a S.M. degree in Economics in 1952 at the Massachusetts Institute of Technology. During 1950 and 1951 he was a Research Assistant in the MIT Department of Mathematics and worked on the application of statistical methods to seismic prospecting. In 1952 he became a Research Associate in the MIT Department of Geology and Geophysics, where he is in charge of operations of the Geophysical Analysis Group.

Mr. Robinson is a member of Sigma Xi, the American Geophysical Union, and the Econometric Society.

G. P. WADSWORTH

G. P. WADSWORTH received his S.B. degree in 1930, S.M. degree in 1931, and his Ph.D. degree in 1933, all in mathematics from the Massachusetts Institute of Technology. Dr. Wadsworth has been on the staff of the Mathematics Department at the Massachusetts Institute of Technology since 1934 and is now an Associate Professor. His original interest in the field of mathematics was in systems of partial differential equations and the geometry of algebraic pfaffians, but later his interest turned toward the field of mathematical statistics. In the last 10 years he has been mainly concerned with problems in Operations Research applied to military and industrial situations and in the application of time series analysis to economic and geophysical data. During the last war, Dr. Wadsworth was a special consultant in the field of weather to the Army Air Forces both in the United States and the European theatre of operations, and also worked with Ordnance on inspection problems. He is a member of the American Mathematical Society, Sigma Xi, the American Meteorological Society and a Fellow of the Operations Research Society of America.

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REPRESENTATIVE ON DIVISION OF GEOLOGY AND GEOGRAPHY NATIONAL RESEARCH COUNCIL

L. L. NETTLETON, Gravity Meter Exploration Co., Houston, Texas (June, 1954)

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the society. This publication does not constitute an election but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the president within thirty days. Names of the references appear in parentheses after the name of each nominee.

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ABSTRACTS OF PAPERS PRESENTED AT THE TWENTY-THIRD ANNUAL MEETING SAM HOUSTON COLISEUM, HOUSTON, TEXAS MARCH 23–26, 1953

Good Ranch Oil Field, Borden County, Texas.

H. C. McCarver, Seaboard Oil Company, Dallas, Texas.

The Good Ranch Field, located in the southwestern part of Borden County, Texas, became an oil producer in April, 1949. The discovery well was drilled subsequent to a seismograph program along a suspected reef trend. The comparison of developed field to original seismic structure, together with subsequent geophysical studies of the producing area, provide material for interesting comments, maps and cross sections.

The Microlog Continuous Dipmeter.

Pierre de Chambrier, Schlumberger Well Surveying Corp., Ridgefield, Connecticut.

Some of the methods used at the present time for the determination of the angle and of the azimuth of the dip of the formations traversed by a bore hole are based on the correlations between three curves recording certain electrical characteristics of the formations, such as S.P. or resistivity, along the wall of the bore hole in three equally spaced azimuths. With the conventional equipment used for the application of these methods, the measurements are made over separate intervals of depth.

In the present paper, a new improved instrument called MicroLog Continuous Dipmeter is described, wherein the three curves used for the determination of the dip are obtained with three MicroLog devices, and wherein these three dipmeter curves, orientation of the instrument and the inclination of the bore hole are simultaneously and continuously recorded.

It is shown that with the help of this instrument numerous dip determinations can be made in a given well, with a higher accuracy and a greater recording speed.

The paper is illustrated with field examples.

Radioactivity Surveying of Shot Hole Cuttings.

W. L. Morris, Hoylman & Morris, Los Angeles, California.

General discussion is given of radioactivity and the problems involved in the use of radioactivity in the search for uranium and other minerals. Different types of instruments and their applicability to surveys of slush pit cuttings and bore holes are discussed.

Seismic Model Study.

E. T. Howes, L. H. Tejada-Flores and L. Randolph, United Geophysical Company, Pasadena, California.

A method has been developed for studying seismic reflections in reduced scale which simulates

geophysical seismic exploration methods. Use is made of a tank of water for transmission of the acoustic wave from a source to a faulted limestone stratum and return to a receiver.

Details of equipment used and slides diagraming the various details along with oscillogram slides of acoustic reflection waves are included.

A Safety Program—Management's Responsibility.

G. H. WESTBY, Seismograph Service Corporation, Tulsa, Oklahoma.

Management, for success, must be concerned with the welfare of its employes, satisfaction of its clients, a suitable profit for its stockholders, and proper third party or public relations. A safety program is one of the many, but one of the most important, management devices for success.

Discussion of a Student Cooperative Work Plan.

CECIL H. GREEN, Geophysical Service Inc., Dallas, Texas.

Effective exploration is a combination of well designed equipment and competent personnel. The latter factor attains special importance as exploration problems become more complex and competition increases with other industries for scientific manpower. A cooperative plan for undergraduate university students is described wherein aptitudes are measured in a guided course of actual exposure to various phases of petroleum exploration.

Problem Areas for the Seismologist.

GLENN M. CONKLIN, Sun Oil Company, Dallas, Texas.

Interpretative problems encountered in four widely scattered areas, South Florida, Beaver County, Oklahoma, the Plainview Basin of the Texas Panhandle, and Hancock County, Mississippi, are discussed.

Secondary refraction records, shot in Okeechobee County, Florida, offer problems because of the low-velocity energy being sustained for long periods of time. This low-velocity energy distorts and obliterates the high-velocity events.

Velocity problems due to differential salt solution in the Blaine-Cimarron interval in Beaver County are considered. Records are shown which illustrate the distortion of events and the resultant problems.

Multiple reflections give trouble in the Plainview Basin of the Texas Panhandle. Record sections showing the many multiples are shown and discussed.

Multiple reflections in Hancock County, Mississippi, are discussed and record sections and cross sections are shown.

Some suggestions for the treatment of the problems are advanced.

Note on the Refracted Wave in a Layer.

FRANK PRESS AND MAURICE EWING, Lamont Geological Observatory, Columbia University, Palisades, New York.

Refraction measurements give representative values for the velocity in a layer only when wavelengths are small compared to the layer thickness. Previous theoretical work on refractions assume an infinitely thick layer. Consideration of the theory for finite layer thickness leads to appropriate conditions on the wavelength when the velocity is to be determined to a prescribed accuracy. At large distances, these conditions arise from interference between the refracted wave and the wave reflected at grazing incidence from the bottom of the layer. Examples are given.

Developments in Continuous Velocity Logging.

R. A. BRODING, G. C. SUMMERS AND J. O. ELY, Magnolia Petroleum Company, Dallas, Texas.

Comparison of velocity data derived from continuous velocity logs with those obtained by con-

ventional geophone surveys indicates that with the present improved velocity logging instruments an accuracy of the order of 1% can be achieved in determination of total travel times from these logs. A simplified field procedure eliminates the need for a seismic crew on such surveys if the travel time to some point a short distance below surface casing can be obtained by the gun perforator technique.

Comparison of velocity with electric and radioactivity logs indicates that in general there is a lack of evidence to support the correlating of the elastic properties with electrical or natural radioactivity properties of rock. Examples of unrelated velocity and electrical resistivity contrasts illustrate the hazards of deriving velocity data from resistivity logs. The lack of correlation between the velocity logs, core analyses, and neutron logs suggests the hazards of correlating porosity or fluid content with velocity. The good correlation that is often observed between an acoustic transmission amplitude log and the neutron log suggests that fluid content may be controlling the transmission amplitude log.

The SIE Electronic Shaking Table.

LOUIS W. ERATH, Southwestern Industrial Electronics Company, Houston, Texas.

The simulation of seismic motion has been a problem of geophysical laboratories for many years. Considerable effort and large sums of money have been spent to effect a solution to this problem, and a great deal of elaborate apparatus has been built. The purpose of this paper is to describe a shaking table which has been developed by the SIE Research and Development Corporation. This new shaking table is believed to be unique and to have many advantages over existing instruments. The SIE Shaking Table is based on electronic and feed-back principles, and all of the advantages which can be obtained from this powerful combination have been exploited. The weight of the seismometer being tested is supported by a magnetic field and displacement is measured by a high frequency sensing element and is displayed by a special cathode-ray indicator. Calibration is accomplished by displacing the table with an ordinary micrometer screw. Excellent transient response allows tape recordings of ground motion and other phenomena to be played into the input circuit of the shaking table which provides the research engineer with a new and more accurate means of evaluating geophysical apparatus.

Stratigraphic Considerations Governing Gravity Interpretation in Utah.

W. H. FENWICK, Fenwick-Walczak Company, Casper, Wyoming.

A practical interpretation of the gravity method of geophysical prospecting is outlined in terms of the geological aspects which might be anticipated in given prospective areas. Schematic geological structural occurrence and their influence upon the method are illustrated. Specific examples of results obtained in local areas of the Uinta Basin and the Salt Valley areas of Utah and their possible geological implications are described. Possible application in other areas, such as the Basin and Range Province, are suggested with reference to the geological influences which may be important.

Curved Path Delta T Analysis.

JOHN T. BRUSTAD, Western Geophysical Company, Los Angeles, California.

A rapid and accurate "curved path" delta-T velocity analysis may be calculated in a simple manner. The average velocities so obtained will, in most cases, be accurate to within ½ of 1% of theoretical, and will, in general, be far more accurate than those calculated using the "straight path" assumption.

The method is based upon a simple relationship: If T is the reflection time at zero offset and $T+M$ is the reflection time at an offset of S feet, then the quantity $K=S^2T/2(M^2+2MT)$ is a close approximation of $\int_0^{1/2T} V^2 dT$. The distance between successive reflecting horizons, under the assumption of constant velocity in the interval, is then given by the square root of the product of the increment in K by half the increment in reflection time. The reflecting depths and corresponding average velocities can then be easily obtained.

Geophysical Progress.

HENRY C. CORTES, Magnolia Petroleum Company, Dallas, Texas.

Histories or reviews covering the period from 1922, the first year of petroleum geophysics in the United States, to 1940, were ably presented by Eckhardt, Macelwane and Weatherby at the Society of Exploration Geophysicists' annual meeting that year. This paper deals mainly with advances in geophysics since 1940.

Marked progress has been made in the amount of geophysical activity, in the number of new oil fields discovered per year based wholly or partially on geophysics, in geophysical techniques, and in education. Improvements in instrumentation, field operational procedures, and interpretation methods have steadily increased the usefulness of the three major methods—seismic, gravity, and magnetic. The development of the aerial magnetometer, especially, and the underwater gravimeter represent notable achievements. These developments have made possible the extension of geophysical activity offshore, and in many other areas previously considered inaccessible.

Research, both fundamental and applied, is being conducted on a greater scale now than in 1940 or prior thereto. Increased geological-geophysical co-ordination has led to better appreciation and utilization of the geophysical methods and has resulted in the discovery of important oil and gas reserves.

Novel or more direct oil finding methods may possibly be discovered or perfected. It is more probable however, that the future of exploration geophysics will be primarily in the continual refinement of the presently known methods. Advances in exploration geophysics and geology, along with teamwork, should insure adequate production and reserves within the United States for a long period. This is predicated on our nation having competitive free enterprise, which has been responsible for the leadership of this country in oil finding, producing, transporting and refining techniques.

Aeromagnetic Anomalies Over Known Structures and Oil Fields.

N. C. STEENLAND, Gravity Meter Exploration Company, Houston, Texas.

A monograph, published in 1949, described a method of determining the depth of the sedimentary thickness overlying the crystalline basement surface, using aeromagnetic data, and included several substantiating examples. Since then, this method has been effectively used over hundreds of thousands of square miles; the general concept has been sufficiently confirmed so that, at this date, structural contour maps of the basement surface can be prepared with some degree of confidence.

Further application of this approach to aeromagnetic interpretation entails the removal of the large, so-called "regional," anomalies upon which the calculations for the sedimentary thickness are made. The residual anomalies then can be sorted into several remaining categories, including, for example, anomalies caused by relief of the basement surface or those that arise from magnetization contrasts within the sedimentary section.

Application of this type of aeromagnetic interpretation are presented over known structures and oil fields in a series of examples representative of several of the major petroleum provinces of the United States, namely, the Williston Basin, The Rocky Mountain basins, and the Midland Basin.

Seismograms as an Aid to Geological Interpretation in the Poza Rica Area.

D. W. ROCKWELL, Geophysical Service, Inc., and ING. ANTONIO GARCIA ROJAS, Petroleos Mexicanos, Mexico, D. F.

The Golden Lane oil fields, located along the crest of a buried Cretaceous barrier reef south of Tampico, have produced 1,120 million barrels to date.

From the initial discovery in 1908 until 1927, production was extended to San Isidro, south of the Tuxpam River, largely on the basis of trend.

Commencing in 1942 a renewed effort, employing gravity and seismic surveys, was made to extend production southward, which culminated in 1952 with a major discovery, the Ezequiel Ordoñez field, about 50 kilometers farther southeast.

The authors show how interpretative problems, stemming principally from reflection data discontinuities, were resolved by coordinated study with sub-surface geologic data. Interpreted in this light, the seismic sections clarify the relationship of the Golden Lane reef to the Poza Rica trend and to its regional setting. They have proved valuable not only for locating Cretaceous reef highs, but also for detailing Tertiary strata overlying and flanking the Cretaceous.

Wavelet Contraction, Wavelet Expansion and the Control of Seismic Resolution.

NORMAN RICKER, Carter Oil Company, Tulsa, Oklahoma.

This paper discusses the transmission characteristics of seismic apparatus for distortionless reproduction of seismic wavelets. It is shown that, by suitable design of seismic apparatus, the individual wavelets which go to make up a seismogram may be contracted or expanded without altering the relative arrival times of the wavelet centers. By means of this procedure the resolving power of the seismic apparatus may be increased or decreased at will, within certain limits. Laboratory studies of the performance of the wavelet contractor are described and field seismograms made with the wavelet contractor also are displayed.

Aerial Shooting for Seismic Exploration.

J. J. JAKOSKY, International Geophysics, Inc., Los Angeles, California.

This paper describes a new technique for air shooting which has recently entered commercial seismic operation.

The first part of the paper presents a brief historical résumé of early work by prior investigators in the use of explosives placed at a height above the earth. The initial proposals utilized explosives at a height comparable to the depth of the reflecting bed below the surface. More recent work utilizes explosives placed within a few feet of the surface of the earth to utilize the supersonic wave energy.

The subject technique uses an explosive bomb which is ejected vertically from a mortar placed on the surface of the ground. The bomb is exploded at a specific height, which is a function primarily of the spread length and near-surface ground velocity, in order to minimize the detrimental effects of ground-roll and reverberation which have created such serious obstacles in previous air shooting techniques. The apparatus and bombs, and general theoretical factors are described.

Records are shown from different surveys comparing the recordings from in-hole shooting with air-shots at the same shotpoint, at various difficult drilling areas in the United States.

The technique has proved to be rapid and to give usable results comparable to in-hole shooting in many areas. The method is particularly attractive where portability is required since the weight of the mortar and its associated equipment is only 57 pounds.

A Velocity Function Including Lithologic Variation.

L. Y. FAUST, Amerada Petroleum Corporation, Tulsa, Oklahoma.

The goal of this investigation was the development of a formula capable of predicting velocity from well logs with the same accuracy attainable by direct measurement. A tentative lithologic parameter was developed using values obtainable from electrologs. A relationship between velocity, depth, geologic time, and the lithologic parameter was determined from a study of these quantities in nearly a million feet of section measured in one hundred and fifty velocity surveys.

The application of the formula in the prediction of vertical travel time indicates that, while the results are encouraging, the goal has not been reached. A study of the errors seems to show that this end might be accomplished in one of two ways: The more complete approach will require the aid of electrolog experts. A practical solution may be presently at hand but would require the cooperation of other velocity investigators.

Ghost Reflections Caused by Energy First Reflected Above the Level of the Shot.

F. A. VAN MELLE AND K. R. WEATHERBURN, Shell Oil Company, Houston, Texas.

A recorded event which has not traveled a simple reflection path, but has undergone a previous

reflection from the base of the weathering or from the surface of the earth above the shotpoint, may, by analogy with optical ghosts, be called a ghost reflection. A method is described for determining the reflection coefficient at interfaces above the level of the shot. Values as high as 0.7 have been found in Beaumont clay surface in Harris County, Texas. With reflection coefficients of this magnitude the ghost reflections influence the character of seismograms noticeably.

Sources of Error in Electrical Prospecting (Read by Title Only).

THOMAS S. WEST, SR., AND THOMAS S. WEST, JR., Blanco Oil Company, San Antonio, Texas.

This paper presents field data secured during the investigation of the Resistolog Method, an alternating current method, the Wenner Method and several of its various modifications. This work provides rather extensive data on surface and near surface inhomogeneities in several areas in Texas, Kentucky, Michigan, and Oklahoma. The principal objective is to make available to workers in this field data on the usual nature and magnitude of shallow inhomogeneities under field conditions in oil productive areas.

Other sources of error are also discussed, such as polarization and natural earth currents in case of direct current methods, and induced eddy currents in case of radio frequency and other alternating current methods.

Evidence of the General Structure of the Gulf Coast from Geophysical Data.

PAUL WEAVER, Gulf Oil Corporation, Houston, Texas.

After geophysical prospecting, principally with torsion balance and magnetometer, had attained a considerable coverage along the north side of the Gulf of Mexico the data available to Barton were interpreted by Barton, Ritz and Hickey as evidence of a Gulf Coast syncline the trough of which lies near the present coast. Additional geophysical information, both from further gravity and magnetic surveys, and from reflection seismograph profiles, suggests that near the coast the structure is homoclinal, at least at the shoreline and for some distance beyond it into the Gulf. The information now available also indicates that there are no striking irregularities in the configuration of the basement across the coastal plain, nor evidence of intrusives, except along the interior margin and in Florida. The geophysical data yield information throughout the area to somewhat greater depths than have been drilled, and are believed to be sufficient to indicate that the sediments above the Louann salt in the Mesozoic and Tertiary are substantially concordant, except for the effects of the movement of the salt into domes. Such movements have resulted in local changes in sedimentation over and adjacent to the present position of the salt in these domes, as have been established by drilling, and which are a feature of certain portions of the Coastal Plain extending from western Alabama to the vicinity of Laredo in southwestern Texas.

A 3-Dimensional Seismic Wave Model with Both Electrical and Visual Observation of Waves.

J. F. EVANS, C. F. HADLEY, J. D. EISLER, AND D. SILVERMAN, Stanolind Oil and Gas Company, Tulsa, Oklahoma.

A seismic wave model employing repetitive piezoelectric initiation and detection of ultrasonic pulses to give stationary oscilloscope patterns which are characteristic of the resulting transient wave motion is described. The design of a piezoelectric transducer assembly suitable for initiating or receiving single highly damped elastic pulses in a solid or a liquid will be given. Multi-trace records are produced with a single detector through the use of a simple photographic technique. An example is given showing reflections in a plexiglas plate. Also, as an aid in wave identification in the model, traveling elastic wave fronts in transparent media have been rendered visually observable by means of a stroboscopic illumination and either of two alternative optical techniques. Required circuits, including modifications of a radar transmitter necessary to produce electrical sparks in air sufficiently short and accurately enough timed to make compressional waves in plexiglas plainly visible, are presented. As examples, photographs will be shown of the transformation of longitudinal waves into

transverse by reflection within plastic blocks, as well as of the progressive advance of a wave front incident at grazing angle against a plexiglas-liquid interface and refracted at the critical angle into the liquid.

A Gravity Survey of Meteor Crater, Arizona.

NORMAN HARDING, Houston Technical Laboratories, AND ROSWELL MILLER III, Princeton, New Jersey.

Forty miles east of Flagstaff, Arizona, is a Crater six hundred feet deep and four thousand feet in diameter that was formed by the impact of a meteorite around 50,000 years ago. A gravity survey was made of the Crater in November, 1951 to determine the location and the approximate mass of the meteorite involved.

*Interpretation of Resistivity Data Over Filled Sinks.**

KENNETH L. COOK AND ROBERT G. VAN NOSTRAND, U. S. Geological Survey.

Satisfactory general solutions of Laplace's equation in both prolate and oblate spheroidal coordinates are used to solve the problem of a resistivity survey over a filled hemispheroidal sink. Various methods of presenting the resistivity data are compared, with special emphasis on the application of these techniques to selected field examples. Conclusions are drawn concerning the value of such theoretical studies and the possibility of making satisfactory approximations. Such approximations of the edge effects are made for (1) a vertical dike in case the width of the sink is small in comparison with its length and depth; and, (2) a vertical fault in case the sink is large in comparison with the electrode separation. A careful study of the Lee and Wenner configurations indicates that the former gives additional information that more than justifies the extra time and expense involved.

Comparison of Navigational Methods.

G. A. ROUSSEL, Offshore Raydist Inc., New Orleans, Louisiana.

Over a period of years, surveying methods on geophysical crews in the Gulf of Mexico have undergone a transition from visual to electronic methods of various types. The particular method varies widely with the accuracy and speed required, the area to be covered, and the distance offshore of this area. The paper cites the fundamental differences between visual, radar, shoran, and phase comparison methods, the accuracies of each, and the differences in operational techniques encountered.

Signal-to-Noise Ratio Improvements by Filtering and Mixing.

HAROLD R. FRANK AND WILLIAM E. N. DOTY, Continental Oil Company, Ponca City, Oklahoma.

The paper is concerned with the signal-to-noise (interference) amplitude ratio of seismograms. The problem of improving the signal-to-noise ratio by means of filtering and mixing is approached quantitatively. Records of known signal-to-noise amplitude ratio and of known frequency content were made employing multiple trace variable area equipment such that identical energy was reproduced and re-recorded through various filtering and mixing schemes and comparisons made. Equipment effects on wavelet character and step out times will be illustrated.

The Geology of Shelder Field, Dimwitt County, Texas.

THOMAS D. BARBER, Stanolind Oil and Gas Company, Corpus Christi, Texas.

Although it has received very little publicity, Shelder Field, discovered in early 1930's should be studied by all geologists and geophysicists because it clearly represents the link between the old oil

* Theoretical material is based largely on work performed by Robert G. Van Nostrand at the University of North Carolina at Chapel Hill in partial fulfillment of the requirenents for the degree of Doctor of Philosophy. Field examples are based on work done by Kenneth L. Cook.

finding method and the new or modern exploration technique. Many recently developed exploratory tools were first introduced experimentally at Shelder Field. In chronological summary the successful culmination of the well-coordinated efforts of the Surface Party, Geiger Counter, Torsion Balance, Magnetometer, Seismograph and Core Drill coverage is described. The productive history of this type of reservoir is graphically demonstrated.

An amazing similarity between the discovery, development and performance of Shelder Field and many fields in the world will be noted.

A Major Oil Company's Safety Program.

C. A. MILLER, The Texas Company, Houston, Texas.

Since safety is a human and economic factor involving our everyday activities—whether it be in industry, on the highways, in the home, or at school—it is a subject of paramount importance to all.

Safety in the petroleum industry, especially among the major companies, has reached a high level of efficiency. The Texas Company has a most comprehensive Safety Program that includes all departments. This program as applied to the Geophysical Division, in particular, will be reviewed. It has reflected a favorable reduction in compensation insurance costs and created a high level of industrial and public relations.

How the National Safety Council Can Help Solve Your Safety Problems.

R. G. BENSON, National Safety Council.

Even in a very specialized operation like exploration the majority of accident causes are common with those found in many other industries. Cooperation with a national agency can avoid duplication of effort. Accident records can be studied on a national scope and comparative analysis made from many angles. Since safety is a "state of mind" any successful attitude influencing program, whether it is in your own particular industry or not, can aid your own safety effort.

When planning a safety program in an association, why not have the benefit of the experience of similar programs, operating successfully in other associations? In safety there are no copyrights, no corporation secrets, no cartels; information is available to everyone. The National Safety Council is merely the means of expediting the procuring of this information from its various sources.

Geophysical Accident Facts.

BART W. SORGE, United Geophysical Company, Pasadena, California.

The latest accident information made available through the Geophysical Accident Exchange will be presented. The results of the recently instituted safety reports to the Tulsa business office of the Society will be discussed. If available, geophysical accident information gathered by the American Petroleum Institute will also be shown.

Accident statistics by themselves do not assure safer operations. However, this information is valuable to aid in planning safety and in judging progress.

Seismic Operations Near Power Lines and Radio Transmitters.

JOHN IMLE, Geophysical Service, Inc., Dallas, Texas.

In this discussion all power lines and even telephone lines are considered hazardous because of (1) induction currents occurring in firing lines and cap leads, (2) contact of firing line or cap leads with energized lines when propelled from the shot hole, (3) contact of other equipment, such as metal stadia rods, metal tamps, shot hole casing, or drill masts, with the energized line.

It is pointed out that electric fences are a common hazard to predetonation of caps as also are ordinary fences not intentionally energized that may have a static charge built upon them or that might have been energized by lightning stroke or by accidental contact with an artificial power source at some distant point.

Also discussed are the hazards of radio transmitters which are not commonly recognized but are nevertheless very real when operations are carried on near the transmitting station.

MINUTES OF ANNUAL BUSINESS MEETING

HOUSTON, TEXAS, MARCH 23, 1953

The Annual Business Meeting of the Society of Exploration Geophysicists was held in the Music Hall at the Coliseum in Houston, Texas, on March 23, 1953. President Curtis H. Johnson called the meeting to order at 2:10 P.M.

Reports of the Secretary-Treasurer, the Program and Arrangements Committee, and the Membership Committee were read and are attached as Exhibits A, B, and C, respectively. Reports of the following Standing and Special Committees were submitted and are attached as exhibits:

Committee	*Chairman*	*Exhibit*
Honors and Awards	Sidon Harris	D
Publications	W. T. Born	E
Distinguished Lectures	M. B. Dobrin	F
Reviews	N. C. Steenland	G
Public Relations	R. C. Dunlap, Jr.	H
Safety	Bart W. Sorge	J
Microcarding	M. B. Dobrin	K
Essay Contests	Fred J. Agnich	L
Glossary	Richard A. Geyer	M
AGI Director	L. L. Nettleton	N
NRC Representative	L. L. Nettleton	O
Nominations	C. H. Johnson	P

The report of the Standing Committee on Geophysical Activity was presented by Chairman E. A. Eckhardt at the morning technical session, and is published elsewhere in this issue. Also, the report of the Standing Committee on Geophysical Education, by Chairman J. B. Macelwane, is published in this issue as "Annual Survey of Geophysical Education, 1952–1953."

President Johnson reviewed the general activity of the Society during the preceding year, summarized the work of the Standing and Special Committees, announced the appointment of Paul L. Lyons as Editor of Geophysical Case Histories, Volume II, announced that application for affiliation by the Casper Geophysical Society and the Toronto University Student Section are being processed, announced that affiliation of the Society of Exploration Geophysicists with the American Association for the Advancement of Science has been effected, and announced the results of the mail ballot for election of officers for 1953–1954.

After announcement of officers-elect, President Johnson informed the members present that both candidates for Vice-President had accepted the nomination with the understanding that the winning candidate would not accept nomination as candidate for President for the year immediately succeeding his term as Vice-President.

Following a short acceptance by the newly elected President, Roy L. Lay, the meeting was adjourned at 3:15 P.M.

CARL L. BRYAN, *Secretary-Treasurer*

EXHIBIT A. REPORT OF SECRETARY-TREASURER

The report of the Secretary covers the period from the Joint Council meeting at Los Angeles on March 25, 1952, to March 23, 1953. Reflecting the increased administrative duties involved in handling the affairs of our rapidly growing Society, the Executive Committee found it necessary to hold three formal meetings during the year, one at Houston on May 29, 1952, one at Fort Worth on November 12 and 15, 1952, and the final one at Houston on March 22, 1953. Other business of the Society was conducted by informal discussion and correspondence.

A total of sixty-six Executive Orders were promulgated, of which fifty-nine concerned membership application, transfer and resignation. The other seven Executive Orders are as follows:

No. 306	June 27, 1952	To authorize and underwrite expenses of the Eastern Regional Meeting in Toronto in the fall of 1952.
No. 309	August 14, 1952	Revision of application reference forms.
No. 311	August 25, 1952	Title of Standing Committee on Publicity changed to "Standing Committee on Public Relations."
No. 312	September 4, 1952	Establishment of method of financing Distinguished Lecture tours.
No. 313	September 12, 1952	Affiliation of Geophysical Society of Oklahoma City as a local section.
No. 319	November 24, 1952	Authorization for purchase of Multigraph and Dictaphone equipment.
No. 320	November 25, 1952	Establishment of policy for advertising rates in *Geophysics*.

A slightly condensed version of the minutes of the Executive Committee meeting of May 29, 1952, appeared in the business office publication, "Doodlings," Volume I, Number 3, June 1952. Following are the essential actions taken at the meeting:

1. Approved arrangements in connection with the 1953 Annual Meeting.
2. Approved publicizing of contributions in furtherance of geophysical education, training and/or public relations.
3. Established policy regarding the 1954 Annual Meeting.
4. Established policy regarding micro-carding of uncopyrighted publications.
5. Established policy of canvassing of local sections for Distinguished Lecture material.

The following major actions were taken by the Executive Committee at the meeting of November 12 and 15, 1952:

1. Approved for submittal to the Council certain amendments to the Bylaws of the Constitution, publication of which subsequently appeared in the January, 1953, issue of *Geophysics*.
2. Approved plans for publication of the Cumulative Index to *Geophysics*.
3. Approved plans for announcement of officer candidates.
4. Approved issuance of separate membership list.
5. Approved appointment of consultants to the Standing Committee on Publications.
6. Approved study of contest for student essays on geophysics.
7. Disapproved offering for sale of life memberships.
8. Disapproved establishment of "special interest" sections in the Society.
9. Disapproved the issuance of a special geophysical directory.

At its meeting of March 22, 1953, the Executive Committee

1. Approved, with certain stipulations, the plan of the Committee on Public Relations for publication of a vocational guidance booklet,
2. Approved, with recommended modifications, the report of the Committee on Essay Contest,
3. Disapproved a contribution to the American Geophysical Union,
4. Officially adopted the crest of the Society of Exploration Geophysicists,
5. Approved the place and time of the 1954 Annual Meeting.

The Treasurer's report covers the calendar year 1952 and presents an estimate of income and expense for the 1953 calendar year. The estimates of income and expense are listed in Table I under the 1953 Budget and may be compared with the actual figures for 1951 and 1952. The 1953 Budget is subject to modification by the Council in its meeting of March 23, 1953.

TABLE I

1951, 1952 OPERATIONS, 1953 BUDGET

	1951	*1952*	*1953 Budget*
Income:			
Membership dues	$20,668.00	$24,403.00	$30,000.00
Geophysics	24,538.88	28,440.57	32,000.00
Geophysical Case Histories	711.05	848.00	700.00
Cumulative Index	77.45	38.00	—
Commissions Received	182.67	1,295.28	1,000.00
Interest Received	125.00	337.11	300.00
Miscellaneous Income		1,428.88	1,000.00
Total Income	$46,303.05	$56,790.84	$65,000.00
Expense:			
Operating Expense	$22,423.05	$31,151.69	$33,000.00
Publications Costs	16,462.16	24,509.28	30,000.00
Total Expense	$38,885.21	$55,660.97	$63,000.00
Net Income	$ 7,417.84	$ 1,129.87	$ 2,000.00

There is a pronounced decrease in net income for 1952 as compared with 1951. Much of this decline in profit arises from increased printing costs plus the increased volume of technical material resulting in a larger *Geophysics*, the latter being of benefit directly to the membership. An analysis of operating expense reveals some increase in almost every category. This may be expected as the Society expands in size and in services to its membership and to the profession.

It should be noted that an increase in advertising rates established by the Executive Committee late in 1952 did not become effective during the period of this report. Furthermore, this factor has been estimated conservatively in the 1953 Budget for the reason that many advertisers contracted advertising space for the entire year at the old rate. The estimate of net profit for the calendar year 1953 therefore does not greatly exceed the actual net profit for 1952.

The balance sheet for December 31, 1952, shows the Society to be in a very strong cash position. Reserves appear to be adequate, and no difficulty is anticipated in financing the publications planned by the Society.

CARL L. BRYAN, *Secretary-Treasurer*

REPORT OF AUDITORS

BROWN & BALA
Certified Public Accountants
1110 Hunt Building
Tulsa 3, Oklahoma
March 7, 1953

To the Executive Committee,
Society of Exploration Geophysicists,
Tulsa, Oklahoma.

We have examined the balance sheet of the Society of Exploration Geophysicists as at December 31, 1952, and the statement of net profit for the year then ended. Our examination was made in ac-

cordance with generally accepted auditing standards and included such tests of the accounting records and such other auditing procedures as we considered necessary in the circumstances except that, as instructed, we did not apply the customary procedure of confirming receivables by direct communication with debtors, nor did we inspect the United States Savings Bonds in the hands of the Secretary-Treasurer in Shreveport, Louisiana, but we secured an affidavit from the Secretary-Treasurer confirming the bonds in his possession.

In our opinion, subject to the foregoing comments relating to receivables and bonds, the accompanying balance sheet and related statement of net profit present fairly the financial position of the society as at December 31, 1952, and the results of its operations for the year, in conformity with generally accepted accounting principles applied on a basis consistent with that of the preceding year.

BROWN & BALA

SOCIETY OF EXPLORATION GEOPHYSICISTS
BALANCE SHEET—DECEMBER 31, 1952

ASSETS

Cash		$22,867.06
Accounts receivable:		
Membership dues	$ 1,148.50	
Other	5,162.05	
	$ 6,310.55	
Less—Allowance for bad debts	700.00	5,610.55
Inventory of publications (see note)		980.60
Investment in United States Savings Bonds, at cost		13,880.00
Office equipment	$ 7,347.06	
Less—Accumulated depreciation	1,774.36	5,572.70
Deferred expenses:		
Agency commissions and library discounts		514.09
		$49,425.00

LIABILITIES

Accounts payable		$ 2,007.39
Deferred income:		
Membership dues—1953	$18,565.85	
Subscriptions to and advertising in *Geophysics*	2,862.48	21,428.33
Surplus:		
Balance, December 31, 1951	$24,859.41	
Net profit for the year, per accompanying statement	1,129.87	25,989.28
		$49,425.00

Note—

The accounts do not reflect the inventory of back numbers, reprints and microcards of Geophysics. The inventory of publications covers the amount expended for the printing of a well index during 1951 and 1952. This is a special publication which is in its development stage and is not ready for distribution.

SOCIETY OF EXPLORATION GEOPHYSICS
STATEMENT OF NET PROFIT
FOR THE YEAR ENDED DECEMBER 31, 1952

Income:			
Membership dues		$24,403.00	
Publications—			
Advertising	$19,136.30		
Subscriptions	6,412.58		
Back numbers	1,910.05		
Microcards of back numbers	841.00		
Reprints	1,043.22		
Geophysical case histories, Vol. I	848.00		
Cumulative index to Geophysics	38.00		
Safety Committee Fund	1,525.65		
Discounts allowed	(902.58)	30,852.22	
Commission on sales of books published by others		1,120.09	
Commission on sales of microcard readers		175.19	
Interest received		337.11	
Miscellaneous		558.23	
Distinguished Lectures Fund		1,355.31	$58,801.15
Expenses and publication costs:			
Salaries—			
Business manager		$ 4,959.00	
Office assistants		5,445.53	
Commissions—			
Advertising—business manager		4,050.76	
Advertising—agencies		2,514.11	
Subscriptions—agencies		520.85	
Office rent		600.00	
Utilities		422.27	
Postage		2,333.37	
Stationery and office supplies		3,950.64	
Telephone and telegraph		511.79	
Auditing		300.00	
Depreciation of office equipment		823.55	
Advertising and subscriptions		515.21	
Provision for bad debts		1,036.66	
Federal insurance contributions tax		136.94	
Annual meeting expense		270.85	
Regional meeting expense		680.28	
Contributions		1,000.00	
Traveling expense		220.57	
Miscellaneous expense		859.31	
Safety Committee Fund		1,070.70	
Distinguished Lectures Fund		939.61	
		$33,162.00	
Publication costs		24,509.28	57,671.28
NET PROFIT			$ 1,129.87

EXHIBIT B. REPORT OF VICE-PRESIDENT

Following is a report of the Vice-President's activities for the year 1952–53:

Regional Program Committees were appointed in April 1952 supplementing District Representatives of Local S.E.G. Sections, the additional committees including Europe, South Texas, South Louisiana, Wyoming, Eastern Region, two Representatives at Large, and Mining. The Standing Committee on Program and Arrangements totals 26 members.

All committee men were acquainted with the necessity of pursuing an aggressive policy toward solicitation of good papers for the Annual Meeting and as a result we had an ample supply of papers from which to choose by December 1st. Papers were selected on the basis of quality and diversified interests. Several papers are included on the annual program that were well received in some of the Regional Meetings and were recommended highly for presentation at the Annual Meeting. All abstracts and other pertinent information regarding the program were edited and arranged according to planning of the Joint Technical Program Committee of A.A.P.G., S.E.P.M. and S.E.G., and were submitted to the printer by January 15, 1953. Considerable detail work was necessary to reach a finalized program.

The General Convention Committee Chairman, Mr. Carleton D. Speed, Jr., appointed your Vice-President one of three Vice-Chairmen of the Joint Convention. My duties as Vice-Chairman have been to meet with the General Chairman, the other Vice-Chairmen and the General Steering Committee comprised of 15 Committee Chairmen, at monthly meetings to discuss the over-all plans of the Annual National Convention, work out all details for each of the three societies, avoid overlap between committees and to make certain nothing has been overlooked that would contribute to the success of the convention.

As Vice-President and Chairman of Program Arrangements for S.E.G., I held numerous conferences and small group meetings with a majority of the individual functioning committees to work out problems and arrive at satisfactory arrangements in so far as S.E.G. is concerned. As a matter of record I am happy to report that S.E.G. is well represented on all of these committees, there being from one to four representatives on each, with S.E.G. members being Chairmen of four of these main functioning committees. Much credit is due the S.E.G. members for their faithful service on these committees as listed in the S.E.G. portion of the printed program for this meeting. There has been excellent cooperation between all three societies, and it has been a pleasure to work with such a fine group of people. I can assure you that much hard work has been put into this convention by an untold number of loyal members of all three societies.

Very truly yours,
ROY L. LAY

EXHIBIT C. REPORT OF THE STANDING COMMITTEE ON MEMBERSHIP

During 1952 all classes of membership in S.E.G. reached new high levels. The record of growth is presented in two tables. The society will continue to grow rapidly in 1953 for 800 membership applications are now in process of approval. The membership committee recommends the organization of student sections in Houston and Los Angeles and increased cooperation between local sections and nearby schools.

Table I shows the number of honorary, life, active, associate and student members at the end of the last four calendar years and the changes during 1952. The increase of 530 during 1952 brings the total to 3,366 members. Student membership, which declined during 1951, went up to 295 at the end of 1952.

TABLE I

S.E.G. MEMBERSHIP 1949–1952

	1949	*1950*	*1951*	*1952*	*Change in 1952*
Honorary	3	3	4	5	1
Life				1	1
Active	1,597	1,674	1,829	2,057	228
Associate	494	603	740	1,008	268
Student	245	285	263	295	32
Total	2,339	2,566	2,836	3,366	530
Increase over preceding year	517	227	270	530	

Table II shows the changes in membership during 1952 in detail. Dr. E. A. Eckhardt became the fifth honorary member and William M. Butler was awarded a life membership for winning the crest design contest. Of the 129 members who were dropped 10 changed occupation, 4 entered military service, 11 resigned without giving any reason, and 104 failed to pay dues. The deaths of six active members and one associate member are noted with regret:

Bert P. Howerton
Jake Moon
James C. Johnson
C. R. Love
J. A. Sharpe
Charles B. Aiken
Everett M. May

TABLE II

CHANGES IN S.E.G. MEMBERSHIP—1952

	Honorary	*Life*	*Active*	*Associate*	*Student*	*Total*
December 31, 1951	4	0	1,829	740	263	2,836
Elected	1	1	261	378	92	733
Dropped	0	0	− 26	− 76	− 27	−129
Transferred to higher grade	0	0	− 1	− 33	− 33	− 67
Deaths	0	0	− 6	− 1	0	− 7
December 31, 1952	5	1	2,057	1,008	295	3,366

The primary recruiting technique was the sending out of application forms to all members in August 1951 with a request to place them in the hands of a friend who might be interested in joining the S.E.G. The results of the canvas are shown in the 1952 membership figures because several months are required to receive, approve, and publish membership applications. The present flood of 800 applications is the result of using this same technique in the fall of 1952. But the membership committee believes that the underlying reasons for growth are the expansion of the prospecting industry to nearly 900 geophysical crews in world wide activity and the increased service provided to members directly by the S.E.G. and indirectly through local sections. The best evidence of increased service to members is the greater size of *Geophysics*. The national society enhanced the programs of local sections by sponsoring two Distinguished Lecture tours. During 1952 Oklahoma City Geophysical Society became the tenth local section. The South Texas Geophysical Society is on the road to becoming a S.E.G. section and members in Casper, Wyoming; Billings, Montana; and Bismarck, North Dakota, have written the Business Manager for advice on how to form local societies.

For the future growth of the society the Membership Committee recommends to the incoming

officers and council that more attention be directed to student sections. The committee believes this is one of the best ways to respond to the challenge presented by Curtis Johnson when he says "Adequate Geophysical Manpower is Our Responsibility." During 1952 The University of Toronto Geophysical Society was organized and became the third active student section, but the University of Tulsa Student Geophysical Society has become inactive and opportunities for student sections in Houston and Los Angeles have not been exploited. The addition of a geology department at Rice Institute will improve the opportunity in Houston. Even where independent student sections are not feasible, local sections can cooperate with the nearest schools. For example the Dallas section meets on the S.M.U. campus, the Tulsa section meets at the University of Tulsa, and the Ark-La-Tex Geophysical Society at Centenary College. Students are invited to the meetings. Local sections can cooperate with professors in providing speakers on geophysical topics for special lectures in regular courses. Such methods will bring S.E.G. members into direct contact with one of the best sources of manpower and should be extended.

Respectfully submitted,
FRANCIS F. CAMPBELL, *Chairman*

EXHIBIT D. REPORT OF THE STANDING COMMITTEE ON HONORS AND AWARDS

During this year the President inaugurated a new plan whereby the oldest member of this Committee is appointed Chairman and correspondence relative to this proposal delayed the appointment of Chairman and the duties of the Committee this year; therefore, there was not time enough to carefully consider the possibility of an Honorary Membership Award this year.

A total of twelve papers were considered this year for the Best Paper Award but the more or less unanimous choice was Mr. Theodor Krey's paper, "Significance of Diffraction in the Investigation of Faults." Runner-up for this award was Mr. K. E. Burg's paper, "Exploration Problems of the Williston Basin."

SIDON HARRIS, *Chairman*

EXHIBIT E. REPORT OF COMMITTEE ON PUBLICATIONS

The members of the Publication Committee for the term 1951–1953 were, R. W. Gemmer, Richard A. Geyer, Cecil H. Green, R. A. Peterson, and W. T. Born, chairman.

The Committee on Publications is charged with the duty of advising and assisting the Editor of *Geophysics*. Fortunately for this Committee our Editor has required little advice and requested very little assistance. Accordingly, your Committee's activities have been confined to advising the Editor regarding the desirability of publishing a number of papers submitted to him and a discussion of one matter of policy referred to us.

The one matter of editorial policy discussed was that regarding the publication of foreign language papers. The Editor raised the following questions:

1. Should we solicit and encourage the submission of papers in foreign languages?
2. Should foreign papers be published in the original language or in English translation?
3. If only English translations are to be published, how should such translations be obtained?

It is the consensus of opinion of this Committee that the Editor should welcome papers submitted in foreign languages, but that we should continue to publish them only in English translation. Recognizing the problems involved in obtaining suitable translations, your Committee recommends that foreign authors be requested to submit an English translation with their original manuscripts when possible, but that this not be made mandatory. We further recommend that the Editor be authorized to engage professional translators when he deems it advisable or necessary. A translation so obtained would not be suitable for publication but could be submitted to qualified referees to enable them to evaluate the paper. If publication is recommended, the Editor could then request a qualified member to edit the translation for publication.

Under the guidance of our outgoing Editor, Mr. Paul Lyons, our publication *Geophysics* has grown tremendously in size and scope. To him, and to his predecessors, the Society owes a debt it can never repay. The amount of time and effort required of our Editor has been constantly increasing. Through my contacts with Mr. Lyons and observation of the amount of editorial work he has done, I am convinced that the Society must soon provide its Editor with competent professional assistance. I therefore recommend that, either the newly appointed Publications Committee, or a Special Committee, be instructed to study this problem immediately, and if their conclusion is the same as mine, to recommend to the Society a specific plan for providing such assistance.

Respectfully submitted,
W. T. BORN, *Chairman*

EXHIBIT F. REPORT OF THE STANDING COMMITTEE ON DISTINGUISHED LECTURES

The Distinguished Lectures Committee, consisting of D. C. Skeels, C. H. Dix, Paul L. Lyons, Peter Dehlinger, Carl Savit, and M. B. Dobrin, Chairman, sponsored two lecture tours for the local sections of the society during the 1952–53 season. The speaker for the first tour was Dr. J. Tuzo Wilson, Professor of Geophysics, University of Toronto, whose lecture was entitled "The Origin of Continents as Deduced from Geological and Geophysical Evidence." For the second tour, conducted jointly by the Society and the A.A.P.G., the lecturer was Dr. Maurice Ewing, Professor of Geology at Columbia University and Director of the University's Lamont Geological Observatory. His subject was "The Atlantic Ocean Basin and its Margins." The society was most fortunate in being able to secure two men of such outstanding distinction to lecture under its auspices.

In the course of Dr. Wilson's tour, which extended from November 18 to December 9, 1952, eleven lectures were given. These were before geophysical groups in Tulsa, Houston, San Antonio, Bakersfield, Los Angeles, Dallas, Fort Worth, Shreveport, Oklahoma City, Denver, and Calgary. In several of the cities the meetings were sponsored jointly by the local geological societies and the geophysical societies. In others, the members of the local geological societies were invited as guests. All of Dr. Wilson's lectures went off as scheduled except for the last two, at Denver and Calgary, where flight cancellations caused by adverse weather conditions made it necessary to reschedule the meetings on rather short notice.

On the same day that Dr. Ewing received his invitation to lecture before the Society's local sections, he also received a letter from the chairman of the Distinguished Lectures Committee of the A.A.P.G. inviting him to go on a lecture tour for that organization. He agreed to accept both invitations provided that he would not have to give more than one lecture in each of those cities where both national societies have local sections. The tour was accordingly set up as a cooperative enterprise of the two national societies with the expenses for each jointly-sponsored lecture to be shared equally by the local geological and geophysical groups involved. This arrangement turned out to be particularly advantageous to the local geophysical societies, which were able to obtain Dr. Ewing's lecture at a much lower cost than would have been possible if the S.E.G. alone had sponsored the tour.

During the course of his seven-week tour, which extended from January 5, to February 21, Dr. Ewing gave 30 lectures, of which twelve were sponsored jointly by local geological and geophysical societies. The joint meetings were held in Shreveport, Tulsa, Oklahoma City, Fort Worth, Dallas, Houston, San Antonio, Midland, Denver, Los Angeles, Bakersfield, and Calgary. In each of these cities, the geophysical society took primary responsibility for planning and arranging the lecture and the speaker's visit. Dr. Ewing had better luck than Dr. Wilson with flying weather and was able to be on hand for all his lectures at the scheduled times.

Ever since the Society established the Distinguished Lecture program, the financing of the lectures on an equitable basis has presented a difficult problem. In September 1952, the Executive Committee approved a new plan, first proposed by R. C. Dunlap, Jr., for paying the expenses incurred by the lecturers. According to this plan, each local section sponsoring a lecture would be assessed a fixed amount, determined by a sliding scale based on section membership, to be applied toward the speaker's overall expenses. A previous canvass of the local sections had indicated that the proposed scale of

charges was considered equitable by all of the sections. If the amount raised in this way would be greater than the speaker's actual expenses, the difference would be set aside in a reserve fund to meet any future deficits that might be incurred. If the amount would come to less than this, the deficit would be made up by the national Society from a reserve fund to be set up for the purpose. Soon after this plan was adopted, the Pacific Coast Section very kindly decided to contribute one-third of its net profits from the 1952 Annual Meeting in Los Angeles—amounting to $513.31—to the Distinguished Lecture Reserve Fund.

In the case of Dr. Wilson's tour, his total expenses were $939.61 while the total amount assessed the local sections was $842.00. The deficit of $97.61 was made up from the Reserve Fund. In the case of Dr. Ewing's tour, it was considered most expedient to allow the A.A.P.G. to assess the local geophysical societies directly in accordance with its own financing plan. Since there were 30 A.A.P.G. groups as compared with twelve under S.E.G. auspices, this appeared to be the simplest way to handle the matter.

On the basis of the Committee's experience during the past year the Chairman is confident that the program is a practical one for the S.E.G. and that the local sections are eager to support the Distinguished Lectures program. He is also convinced that it is not really difficult to find able speakers who are willing to take time from their regular activities, at considerable personal sacrifice, to go on lecture tours under Society auspices. The enthusiastic reception which both Dr. Wilson and Dr. Ewing were given by all the local geophysical sections should establish the fact that practical exploration geophysicists have a strong interest in learning about the more academic phases of their subject, so that future committees should have no compunctions about inviting suitable speakers from the academic world.

Our experiment in joint sponsorship of a tour with the A.A.P.G. worked out so successfully that consideration should be given to arranging further tours under the same auspices. Perhaps it would be feasible for the Society in cooperation with the A.A.P.G. to offer two lectures every year on the same basis as this year: one lecture, of interest primarily to geophysicists, for the local geophysical groups alone; the other, of interest to geologists and geophysicists alike, for joint sponsorship by the Distinguished Lectures Committees of both national societies.

One problem that will face the next Distinguished Lectures Committee is whether to maintain the scale of assessment for the lectures as established this year. If the contribution of the Pacific Coast Section were drawn upon, the scale could be reduced considerably for at least one year. It seems more prudent, however, to maintain the scale for at least one more year, until more experience is accumulated with the various financial aspects of the program under the present plan, and then to plan a reconsideration on the basis of the experience to that time. Meanwhile, thought might be given to the feasibility of the Society's using a small part of the reserve fund to offer the lectures to university geophysical or geological groups not located near cities where there are local sections which would be likely to bring the lectures anyway.

The Chairman wishes to take this opportunity to thank our two lecturers for their very considerable contribution in going on tour for the Society, to Mr. R. E. Rettger, Chairman of the Distinguished Lectures Committee of the A.A.P.G. for his willing cooperation with our Committee in arranging the jointly sponsored tour, to the presidents and program chairmen of all the local societies, for their assistance in the Committee's work, and to Colin Campbell for help of many kinds.

MILTON B. DOBRIN, *Chairman*

EXHIBIT G. REPORT OF THE STANDING COMMITTEE ON REVIEWS

The Reviews Committee appointed in 1951 by the Executive Committee completes its two years of service this month. The membership, in addition to the Chairman, has been K. L. Cook, M. B. Dobrin, T. A. Elkins, E. W. Frowe, R. A. Geyer, L. G. Howell, D. S. Hughes, N. Ricker, R. A. Stehr, I. Tolstoy, and R. J. Watson. In addition, guest reviews were written by Jack E. Oliver, Irving M. Griffin, Jr., W. T. Born, C. Meade Patterson, J. Laurence Kulp, Mark D. Butler, W. Jacque Jost, William Donn, Eugene G. Leonardon, Marcellus H. Stow, J. H. Russell, M. M. Slotnick, and Robert E. Fearon. The co-operation of the guest reviewers is especially appreciated.

The Annual Report given at this time last year covered the reviews written by the committee for the three issues of *Geophysics* for July 1951, October 1951, and January 1952. At that time, 17 books had been reviewed and 14 articles. Since then, 17 books and 26 articles have been reviewed in five issues. Therefore, eight issues of *Geophysics* have averaged slightly over nine reviews per issue.

The breakdown of the number of reviews according to subject matter shows that 17 were on seismic subjects, 9½ on gravity, 6½ on magnetics, 4 on radioactivity, 1 on electrical, 3 on general geophysics, 18 on geology, and 15 on miscellaneous subjects.

The committee has tried to keep the Society abreast of publications that they might not otherwise notice, and this especially entailed a survey of foreign literature. Publications were continuously received from Germany, Italy, Mexico, Japan, England, Ireland, and, at first, some of the Soviet dominated countries. The latter were discontinued at the request of the Reviews Chairman after approximately one year's time when it was apparent that no genuinely technical articles were contained in those publications.

In general, it may be said that the foreign geophysical profession has not recovered from the serious interruption to geophysical development and exploration occasioned by World War II if the material of the foreign publications is any indication. The lack of reviews on foreign technical articles is the result of the scarcity of reviewable material and is not the result of neglect of the foreign publications.

It is hoped that the committee has been successful in stimulating interest in new fields of activity and in new ideas, but there is no concrete evidence on hand to indicate that the effort was successful. More exactly, the Chairman is somewhat surprised at the lack of discussion of some of the more debatable material that has been reviewed, and he hopes that this is a reflection of a lack of time on the part of the membership rather than a lack of interest.

The Chairman is sincerely grateful for this opportunity to express his thankfulness to the members of the committee to whom he has delegated most of the work. The Chairman has reviewed material himself only when it seemed necessary to supplement the reviews received from the membership. Paul Lyons, the Editor, is to be especially commended for his wholehearted support of the committee and for permitting the committee to act with complete confidence. Colin Campbell is also to be thanked for sending the many publications to the Chairman for distribution and for his wholehearted cooperation in any matters pertaining to the committee's work. Lastly, the publisher of *Geophysics* is to be commended for his accurate and attractive handling of the Review Section.

NELSON C. STEENLAND, *Chairman*

EXHIBIT H. REPORT OF THE STANDING COMMITTEE ON PUBLIC RELATIONS

This report covers the Committee's activities since September 1952 when the undersigned was appointed Chairman.

The initial project considered was a vocational guidance booklet to be prepared and distributed by the Society. Preliminary investigation revealed that very little has been done to present geophysics to the high school senior and college freshman. After consultation with President Curtis H. Johnson, this project became a definite aim of the Committee. Progress has been made to the extent that preliminary layout and copy for a 16-page booklet have been presented for critical comment. If the Executive Committee approves the project, the booklet should be ready for distribution by May 1953.

Two other projects were considered by the Committee. The first of these concerned a cooperative effort to be sponsored by the Society and industry aimed at improved relations between the exploration geophysicists and the public. A basic proposal will be offered for consideration by the 1953–1954 Committee.

It also has been suggested the Society prepare and distribute a directory for visual education in geophysics. We recommend the 1953–1954 Committee consider this project.

Respectfully submitted,

R. C. DUNLAP, JR., *Chairman*

EXHIBIT J. REPORT OF THE SPECIAL COMMITTEE ON SAFETY

The special Committee on Safety was continued for another year as a result of actions taken at the annual Council meeting in Los Angeles, March 25, 1952. It was also decided at that time to take the necessary steps to make the Committee a Standing Committee following the next annual meeting in March, 1953, at Houston, Texas.

The present members of the Committee are:

H. C. Bickel, 113—16th Avenue, N.W., Calgary, Alberta, Canada
W. H. Hawkes, Stanolind Oil & Gas Company, P. O. Box 40, Casper, Wyoming
John Imle, Geophysical Service, Inc., 6000 Lemmon Avenue, Dallas, Texas
Charles C. Mason, Humble Oil & Refining Company, Box 1600, Midland, Texas
W. H. Newton, General Geophysical Company, 2514 Gulf Building, Houston, Texas
Frank Searcy, Continental Oil Company, P. O. Drawer 1267, Ponca City, Oklahoma
Bart W. Sorge, *Chairman*, United Geophysical Company, 1200 So. Marengo, Pasadena, California

During the year the Committee has continued its effort to further the cause of safety and accident prevention among geophysical operators. It has tried diligently to interest geophysical operators in incorporating safety programs into their operations, and in many cases members of the Committee have helped companies to set up such safety programs.

We have continued our efforts to collect pertinent safety posters applicable to the geophysical industry, and have continued to make these available to everyone on a non-profit basis through the Tulsa business office of the Society. At the present time nearly 14,000 copies of various posters have been sold. Approximately 50 different posters, applicable to geophysical operation, are now available.

The Committee has continued its cooperation with the Bureau of Mines, the American Petroleum Institute, and the National Safety Council in order to secure for these organizations more complete statistical accident information from our industry. Oil companies operating geophysical crews have always submitted their safety statistics through their safety departments to these recognized safety agencies. The number of geophysical operators submitting these statistics has increased from 3 to 35, an increase of over 1,000 per cent, due to our efforts. We hope to improve this situation still further.

As a result of more statistical safety information being available, it has become apparent that the Exploration classification used by the safety agencies is not suitable due to the fact that it includes many other activities in connection with oil company exploration which are not as hazardous as geophysical operations. This fact distorts the statistics reported by oil companies and makes a comparison less valuable.

As a result of a recent questionnaire, 73 per cent of the 93 organizations replying agreed that the Committee should gather geophysical exploration safety statistics through the Tulsa business office. This has been initiated and will begin as soon as information from January, 1953, becomes available. The information gathered will be made available on a bimonthly basis by being published in the booklet, *Exploration Safety Tips*.

In order to help geophysical operators maintain an interest in safety and accident prevention among their employees, two safety booklets are being published on a non-profit basis by the Committee. The booklet *Doodlebuggin' the Safe Way* is issued quarterly and contains material of interest to all employees on geophysical field parties. The booklet *Exploration Safety Tips* is issued on a bimonthly basis and contains all available safety information and is designed particularly for those on geophysical field parties responsible for safety and accident prevention planning. Mr. John K. Ellis of the United Geophysical Company is the editor of *Doodlebuggin' the Safe Way*, and Mr. J. Doyle Settle, Secretary of the American Association of Oilwell Drilling Contractors, is editor of *Exploration Safety Tips*.

Safety sessions, during which interesting papers on the subject of safety and accident prevention were presented, were held in connection with all regional meetings. The attendance at these sessions

has been increasing and indicates an interest on the part of geophysical operators in the problems of safety and accident prevention.

A complete all-afternoon session wholly devoted to safety will be held in connection with the annual meeting in Houston. In addition, the president of one of the larger geophysical contracting companies will present a paper on management's responsibility for safety at the general session Monday morning.

During the year the problem of possible legal complications for the Society resulting from our activities has been eliminated. Legal advice obtained by the Society indicates that it is very unlikely that the Society would incur any legal liabilities since all of our activities are only in an advisory capacity, and also due to the fact that we have no means of enforcing any rules or suggestions for safety that we might make. As a result, the Committee has received permission from the Executive Committee of the Society to sponsor the Geophysical Accident Information Exchange. This endeavor was initially started by the members of the Committee a year ago as individuals to make certain that no harm would result to the Society. At the present time 23 geophysical organizations are participating in this Geophysical Accident Information Exchange. Statistical information from the Exchange is being presented at meetings from time to time, and will also appear in the booklet *Exploration Safety Tips*. The information gathered through the Exchange has been very valuable in planning effective safety and accident prevention measures. The information has shown that geophysical accidents which happen are very similar and fall into very definite classifications. It has been determined that drillers and their helpers have nearly 50 per cent of all the accidents that occur in geophysical operations.

Information submitted by geophysical operators for 1951 to the American Petroleum Institute shows that geophysical contract operators have a higher lost-time personal injury frequency than any other industrial group listed by the National Safety Council. Since nearly 50 per cent of all geophysical accidents occur in connection with shot hole drilling, the geophysical shot hole drilling contractors appear to have a much worse safety record than that of geophysical organizations. When the Committee received information recently that several employees of geophysical shot hole drilling contractors were killed as a result of their work during the last few months, it was decided that we must take steps to interest geophysical shot hole drilling contractors in the importance of intensive and intelligent safety efforts. This is necessary since in many states geophysical shot hole drilling contractors and geophysical operators are grouped into one category for purposes of establishing manual insurance rates. A letter was recently sent to all geophysical drilling contractors listed in the Geophysical Directory. In this letter we outlined what the Committee is doing in respect to geophysical exploration safety, and asked for comments as to what we could do to help them improve their safety record. At the date of the writing of this report only six replies have been received. It is our plan to follow up this matter shortly with a definite offer of help based on the replies received so far.

The Committee is presently gathering a mailing list of all individual members of the Society interested in safety and accident prevention. It is felt that this is necessary since working with geophysical operators alone has not produced sufficient results. Of necessity, the safety and accident prevention efforts in the geophysical industry must be cooperative to be successful. For this reason, it is essential that the Committee take all necessary steps to improve this cooperation.

The present members of the Committee on Safety feel that our efforts so far have been worth while and that we are finally beginning to show results. Therefore, it is our recommendation that this Committee be made a Standing Committee at the next annual meeting so that our efforts towards greater industry-wide safety efforts may be continued.

Respectfully submitted,
BART W. SORGE, *Chairman*

EXHIBIT K. REPORT OF THE SPECIAL COMMITTEE ON MICROCARDING OF GEOPHYSICAL LITERATURE

At its 1952 Annual Meeting, the Council voted that the Society should underwrite the reproduction on microcards of the complete back files of twelve geophysical journals, the cards to be offered

for sale to various industrial and university libraries by the Microcard Foundation. The special committee which had been appointed to investigate and make recommendations on this project has been reappointed by the President of the Society to handle liaison with the Microcard Foundation in the production and marketing of the microcards. This Committee consists of R. A. Geyer, Carl L. Bryan, and Milton B. Dobrin, Chairman.

In arranging for publication of the microcards, it was necessary to secure permission from the publishers of all of the original journals which were copyrighted in this country. In most cases, this permission was granted quite willingly, although in several instances a considerable amount of correspondence was necessary to secure an arrangement agreeable to all concerned, and in the case of one journal, *Geofisica Pura e Applicada*, permission was flatly denied. This journal was accordingly removed from the list of those to be reproduced.

The Microcard Foundation has undertaken the responsibility of borrowing the original journals from libraries holding them and of sending them to the microcard printing plant in La Crosse, Wisconsin, for reproduction. To locate the originals of many of the scarcer journals turned out to be a large-scale project which required a great deal of correspondence. Many of the sets, after being borrowed, were found to be incomplete and other loans of the same title had to be sought.

As of March 4, complete sets of microcards have been photographed for two journals and complete volumes for four other journals are at La Crosse in the process of being reproduced. Original volumes for four more journals have been requested and these should be received at La Crosse and reproduced on microcards by the end of March. It is thus expected that the complete series of microcards should be available from the Microcard Foundation by April 1. As soon as the Foundation decides on the prices it will charge for the various sets, all those companies, universities, and others who expressed an interest in purchasing the microcards will be advised which cards are available and at what price.

The Society has committed itself to guarantee the sale of ten sets of microcards for each of the journals within three months of the time they are made available. In view of the very considerable demand which has been indicated for this literature in the Committee's 1952 canvass, it appears most unlikely that the Society will be called upon to buy any unsold sets.

The Chairman wishes to express his appreciation to Dr. Fremont Rider and Miss Grace W. Bacon of the Microcard Foundation for the considerable effort they have expended in completing this project so successfully, also to Colin Campbell for handling much of the correspondence and other work in connection with this project.

M. B. DOBRIN, *Chairman*

EXHIBIT L. REPORT OF THE SPECIAL COMMITTEE ON STUDENT ESSAY CONTESTS

This Special Committee was appointed by the President about the middle of February 1953 and consists of the following members:

Dr. John C. Hollister
Colorado School of Mines, Golden, Colorado
Rev. J. B. Macelwane, S.J.
Saint Louis University, St. Louis, Missouri
Mr. E. A. Pielmeier
United Geophysical Company, Pasadena, California
Mr. Fred J. Agnich (Chairman)
Geophysical Service Inc., Dallas, Texas
Dr. M. M. Slotnick
Humble Oil & Refining Company, Houston, Texas
Mr. Hugh M. Thralls
Seismograph Service Corporation, Tulsa, Oklahoma
Dr. J. Tuzo Wilson
University of Toronto, Toronto, Ontario, Canada

In the short length of time available to it, the Committee has not been able to do more than generally explore the subject and come up with some recommendations for a future course of action. The members were not all unanimously agreed on all points, but no serious divergence of opinion was present. The members of the Committee were, however, all of the opinion that the Society should conduct a Student Essay Contest and that every effort should be made to place it into operation during the coming year.

The following recommendations are made by this Committee:

1. *Eligibility*

   The Student Essay Contest will be open to all university students with an interest in geophysics (taking at least one course) and with no restriction as to membership in the S.E.G. or affiliated groups.

2. *Subject Matter*

   No restriction; may be scientific, expository, economic or philosophical, but must relate to geophysical exploration.

3. *Length*

   Wide latitude, but not to exceed a maximum of 5000 words, including the abstract.

4. *Number of Prizes*

   Three prizes, duplicated in each of two groups—undergraduate and graduate university students. Results published in *Geophysics*.

5. *Nature of Prizes*

   First Prize
   a. Trip to the National Meeting with payment of transportation, plus allowance for room and food expenses.
   b. Cash award of $100.00.
   c. Suitable medal or plaque presented formally at the National Meeting.
   d. Publication of paper in *Geophysics*.

   Second Prize
   a. Cash award of $100.00.
   b. Suitable medal or plaque.
   c. Paper may or may not be published in *Geophysics*.

   Third Prize
   a. Cash award of $50.00.
   b. Suitable medal or plaque.

   Expense of prizes to be obtained from special fund supported by Industry anonymously.

6. *Judging*

   This will be accomplished by a Student Essay "Standing" Committee comprising three men appointed by the President of the Society as each of their three year terms expire, plus the Editor of the Society. The Committee will not be obliged to make any or all awards in event of insufficient entrants or quality below a reasonable standard. The Committee will be expected to adopt and to publicize certain general instructions.

This Committee recommends that a Standing Committee be appointed by the President immediately so that the plan may be formalized and specifications set this summer in order that our first Student Essay Contest may get under way during the early part of the next school year.

The Committee wishes to thank Mr. Cecil H. Green for his efforts in recapitulating the ideas of the various members of the Committee while the Chairman was out of town and unable to do any work.

Respectfully submitted,
FRED J. AGNICH, *Chairman*

EXHIBIT M. REPORT OF S.E.G. GLOSSARY COMMITTEE

The activities of the S.E.G. Glossary Committee during the past year have been confined primarily to organizing its project so that the Local Sections could participate efficiently in this work. It was agreed that each of the participating Local Sections was to be assigned one or two letters of the alphabet for their share. In this way, the work of completing the Glossary would be kept to a minimum for any one group within the Society.

Eleven Local Sections have assumed the responsibility for completing the Glossary Project. The appropriate number of subcommittees were organized with the S.E.G. Representative of the Main Committee acting as coordinator in assigning certain letters of the alphabet to each Local Section and keeping them informed of the progress and activities of the other participating earth-science Societies. At the moment, only one of the Local Sections, namely the Ark-La-Tex, has completed its assignment: in this case for the letters "T" and "V." However, replies to a recent letter to the Chairmen of the subcommittees indicate that several more are expected to be completed by the time of the annual meeting. It is hoped that the remainder will be available in the not too distant future.

A substantial grant, totaling $15,000 has been allocated to the Main Committee by the National Science Foundation and the Geological Society of America. This fund is to be used to help cover the necessary expenses in the preparation of the complete glossary covering all the major Earth Sciences. Plans for the coming year for the S.E.G.'s portion of this project include the final assembling of all the portions of the Glossary submitted by the Local Sections into a unified form. During the course of this work it will be necessary to make certain decisions regarding usage and definition of a number of controversial words. To complete this phase of the work in a minimum of time, it is hoped that the Glossary Subcommittee of the various Local Sections now participating will not be disbanded.

The Chairman of the S.E.G. Glossary Committee is most appreciative of the cooperation which he has received from the various members of the Local Societies who have participated in this project as well as the encouragement and aid given him by the Society President, Curtis H. Johnson, and the Business Manager, Colin Campbell.

RICHARD A. GEYER, *Chairman*

EXHIBIT N. REPORT OF DIRECTOR OF AMERICAN GEOLOGICAL INSTITUTE

The term of the undersigned as a Director of the American Geological Institute representing the Society of Exploration Geophysicists expired with the Annual Meeting of the Institute on November 13, 1952. The current Directors are Andrew Gilmour and George E. Wagoner. Since his last report, this Director has represented the Society of Exploration Geophysicists at the American Geological Institute Directors' meeting of March 23, 1952, in Los Angeles, and November 13, 1952, in Boston.

The following paragraphs outline the more important activities of the Institute as carried out at the meetings of the directors and of officers and by the office of the Executive Director.

The Institute suffered a severe loss in the resignation of David Delo as Executive Director, which became effective July 18, 1952. Dr. Delo has become President of Wagner College, Staten Island, New York. A committee appointed for the selection of a new Executive Director was composed of Dr. E. A. Eckhardt, Chairman; John Rouse and K. K. Landes of A.A.P.G., Wendell Woodring and H. R. Aldrich of G.S.A. Their task turned out to be very difficult as several promising contacts were unable, for one reason or another, to accept the position. However, the position has been filled as of January 1, 1953, by Dr. Robert W. Webb, who is on leave of absence from his position as Professor of Geology, Department of Physical Sciences, Santa Barbara College of the University of California.

The new officers of the Institute, elected at the Boston directors' meeting, are: Carey Croneis, President (re-elected); W. C. Krumbein, Vice-President; Harry S. Ladd, Secretary-Treasurer (re-elected).

The activities of the Financial Committee, Roger Denison, Chairman, have come in for considerable discussion. A recent campaign to solicit contributions from industries using geology, while not as successful as had been hoped for, has given promise of enough support to carry the Institute for the immediate future. However, the problem of permanent financing is still a serious one.

A committee for the preparation of a glossary of geologic terms, J. V. Howell, Chairman, now has sub-committees in each of the constituent societies to provide lists of words and to cross check the lists prepared by other societies. Dr. R. A. Geyer is Chairman for the Society of Exploration Geophysicists. Support totaling $15,000 for compiling and initial costs of publication has been received from the Geological Society of America (to be reimbursed from sale of the publication) and from the National Science Foundation.

The geological information committee, F. W. Rolshausen, Chairman, has completed the compilation of the first highway strip log which covers Highway 75, from Galveston to Dallas, and Highway 77, from Dallas to the Red River. This has been published by the Houston Geological Society, who have it on sale for $1.50.

There is underway a proposal to set up a Scientific Manpower Commission, which is similar to but does not overlap the Engineering Manpower Commission. The proposed commission would be governed by two "Incorporators" from each of the Institutes or Societies represented so as to cover the field of professional scientists in a manner similar to that in which the professional engineers are covered by the Engineering Manpower Commission. Ernst Cloos and Harry S. Ladd were designated as "Incorporators" for the American Geological Institute.

The Committee on Geological Personnel, William B. Heroy, Acting Chairman, has summarized the present status of geological personnel. As reported at the Boston meeting, this summary includes a grouping of geologists by age, by specialization and by employment status; growth of membership in societies, and a projection of the normal needs and anticipated demands for geologists based largely upon the compilations of A. I. Leverson.

A committee on geology in American colleges and universities, Sheldon Judson, Chairman, reviewed the colleges which do and which do not offer courses in geology, the status of geological sciences in high school, conferences on geology in secondary schools, radio and television programs which have included geological subjects and a recently completed Boy Scout geology merit badge with its booklet prepared by prominent geologists.

Plans for expansion of the Institute News Letter into a bi-monthly magazine of general interest to the profession were interrupted by the resignation of Dr. Delo, who had done much preliminary work.

The meeting of the Directors of the Institute, which will be held in Houston on March 23rd at 1:30 P.M. and at 8:00 P.M., Room E, Rice Hotel, will be a crucial one for the future of the Institute.

Representation of the Society of Exploration Geophysicists at the Directors' meetings for the past three years has been almost entirely by myself, only one other director having attended any meetings in that time. It is strongly urged that the current directors be encouraged to take an active part in representing the Society and to keep the Society informed of the progress of the Institute and any of its activities which are of interest to members of the Society of Exploration Geophysicists. In this connection, it is recommended that the practice of preparing a short note of current activities of the Institute for publication in each issue of *Geophysics* be continued in order that readers be kept informed of Institute actions which are of interest to the Society.

L. L. NETTLETON, *Ex-Director*, American Geological Institute

EXHIBIT O. REPORT OF MEMBER, DIVISION OF GEOLOGY AND GEOGRAPHY, NATIONAL RESEARCH COUNCIL, REPRESENTING THE SOCIETY OF EXPLORATION GEOPHYSICISTS

The Society of Exploration Geophysicists is one of the fourteen constituent societies of the Division of Geology and Geography of the National Research Council, of which W. W. Rubey, U. S. Geological Survey, is President. The constituent societies are as follows:

Am. Geog. Soc.	Seis. Soc. Amer.	G.S.A.
Am. Geophys. Union	A.A.P.G.	Soc. Vert. Paleont.
Assoc. Amer. Geog.	Min. Soc. Am.	Soc. Econ. Geol.
Am. Soc. Photogram.	Paleon. Soc.	Soc. Expl. Geophys.
Am. Cong. Surv. & Map.	S.E.P.M.	

Chairman of the Division is Ernst Cloos, Professor of Geology at Johns Hopkins University.

The Division of Geology and Geography is one of eight divisions which cover the fields of Anthropology and Psychology, Biology and Agriculture, Chemistry and Chemical Technology, Engineering and Industrial Research, Geology and Geography, Mathematics, Medical Science, and Physical Sciences, with each division having from two to thirty constituent societies.

The Division of Geology and Geography held a meeting in Washington on May 3, 1952, which your member was unable to attend. A major item on the agenda of this meeting was a conference on "What can geology and geophysics contribute to improve the national resources picture?"

Your member, whose term extends to June 30, 1954, hopes to attend other meetings of the division and will be kept informed of actions of the division through a considerable amount of paper which comes to his attention.

L. L. NETTLETON,
Member, Division of Geology and Geography
National Research Council

EXHIBIT P. REPORT OF THE STANDING COMMITTEE ON NOMINATIONS

The standing Committee on Nominations, consisting of the President of the Society, who acts as Chairman, the Past President, and the Prior Past President, chooses nominees for Society offices as specified in the Constitution and By-Laws. The nominees chosen for the 1953–54 term of office are as follows:

For President:
Roy L. Lay (elected)
Kenneth E. Burg

For Vice-President:
Karl Dyk (elected)
Eugene Frowe

For Secretary-Treasurer:
Bart W. Sorge (elected)
W. B. Robinson

For Editor:
Milton B. Dobrin (elected)
L. Y. Faust

The outgoing Committee has introduced one change in nomination procedures which it hopes will lead to more equitable elections in the future. For more than a decade, the incumbent Vice-President of the Society has been one of the two presidential nominees in the election taking place during his term of office. Each year, during this period, he has won the election. This precedent has become so firmly established that it has become almost embarrassing for the Committee to ask anyone to run for President against the incumbent Vice-President. Moreover it is becoming increasingly difficult to find anyone of proper stature who is willing to accept such a nomination when the precedent against his winning is so strong.

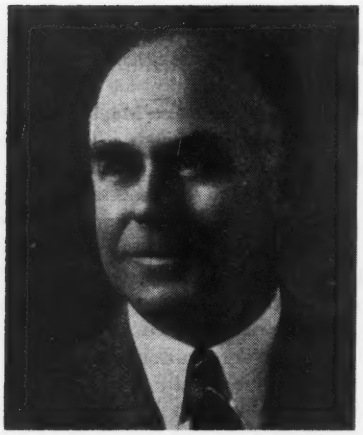
As one solution to this problem, a constitutional amendment has been proposed that would allow the Vice-President to be run for the presidency without opposition. This proposal was considered unsatisfactory for a number of reasons. The final decision was to set up a new stipulation that neither of the presidential nominees in the future be the incumbent Vice-President. The Committee's two choices for the 1953–54 vice-presidential nominations were accordingly advised, upon being offered their nominations, that the winner would not be nominated for President the following year. Both were gracious enough to accept the nominations with this understanding.

It is no part of the Nominating Committee's intention to lose to the Society the benefit of the Vice-President's experience on the Executive Committee and the Committee strongly recommends that future committees give serious consideration to Vice-Presidents of earlier years in choosing nominees for the presidency.

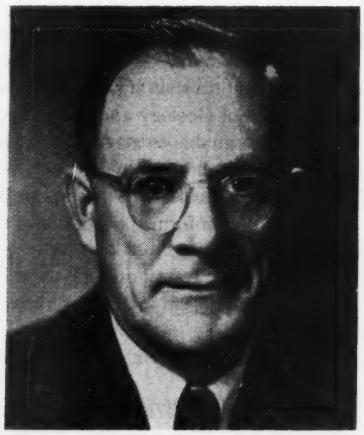
The Committee on Nominations feels that this innovation will increase interest in the elections among the Society's membership and will allow the members a wider choice in selecting their officers from the large body of well-qualified individuals who are, fortunately, available for such service.

CURTIS H. JOHNSON, *Chairman*

OFFICERS FOR THE YEAR ENDING APRIL, 1954



CURTIS H. JOHNSON, Past President



KARL DYK, Vice-President

ROY L. LAY, President

BART W. SORGE, Secretary-Treasurer

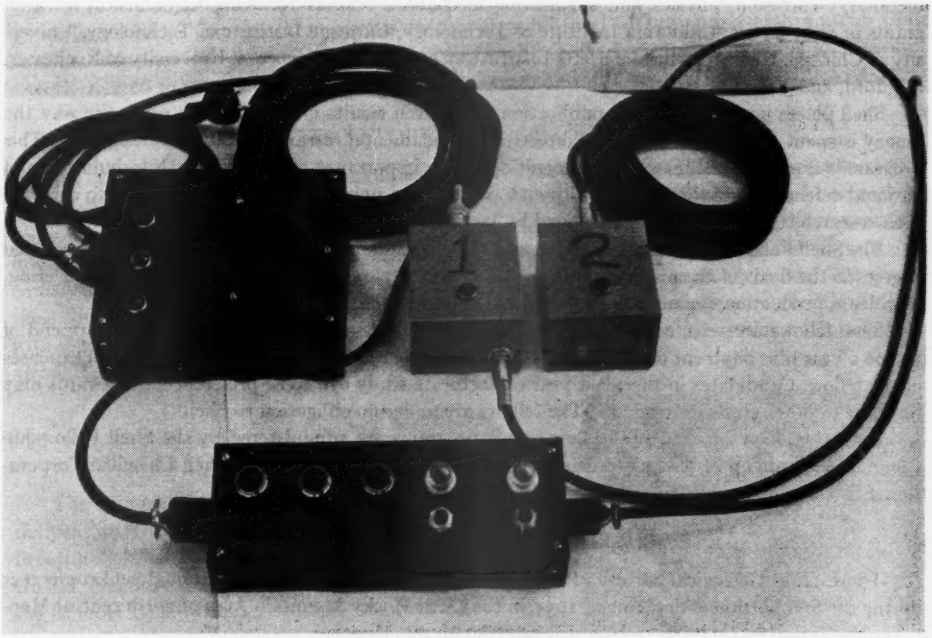
MILTON B. DOBRIN, Editor

ANNOUNCEMENTS

SPEAKERS' TIMING AND SIGNALING EQUIPMENT DONATED

The excellent timing and signaling equipment designed by the Technical Equipment Committee for use during the Joint Annual Meeting in Houston has been made available by the committee for all annual and regional meetings of the AAPG, SEPM, and SEG. Eugene W. Frowe, of Robert H. Ray Co., whose laboratories constructed the instruments, has assembled the three sets and boxed them for portability. The equipment has been placed at SEG headquarters, 624 South Cheyenne, Tulsa, Oklahoma.

Planners of regional or annual meetings of any of the three exploration societies are invited to contact the SEG business manager regarding use of the equipment. One of the sets is pictured below.



Speakers' timing and signaling equipment.

The speaker's timing and signaling equipment is designed to facilitate and simplify the work of the chairman in keeping programs on schedule. The timer is mechanically operated and is set to the time required. Three small lights on the timer are green to indicate more than three minutes time remaining, amber to indicate three minutes time, and red to indicate that the allocated time has been reached. Similar green, amber and red lights are mounted on the speaker's signaling position to let him know the time interval remaining in his speech.

The speaker can control the changing of slides by the projectionist by two small push buttons mounted on the speaker's signal control. These push buttons are numbered 1 and 2 and are connected to the projectionist's signal box by a three conductor electrical cable. There are two signal light boxes, one for each projector, which are numbered one and two. When the speaker pushes button No. 1 on his control, a red light flashes on the projectionist signal box to indicate that a change in slides is requested.

Interconnecting cables are provided such that it is impossible to hook up the equipment incorrectly. AC power at 110 volts is provided through a six foot cord on the chairman's timer unit. In operating the equipment, it is recommended that the timer be turned to the 15-minute point at least and then turned back if used for a shorter period of time. For example, if the chairman is conducting a discussion period of 10 minutes, he will turn the timer to the 15-minute point and then turn it

back to the 10-minute point to properly operate the spring mechanism of the clock. The timer is designed for a maximum of 55 minutes.

RESEARCH AND FELLOWSHIP PROGRAMS RENEWED BY SHELL FOR 1953–54

A 15 percent increase in the Shell research and fellowship programs for 1953–54 was announced today by the Shell organization. The total cost next year will be $177,500. It was $155,000 this year.

The number of fundamental research grants will increase from 12 to 14, with costs rising from $60,000 to $70,000. The number of fellowships will rise from 45 to 48, with the cost of this program increasing from $95,000 to $107,500.

Research grants, at $5,000 each, are made directly to university science departments to aid them in conducting basic research in chemistry, chemical engineering, geology, mechanical engineering, metallurgy-corrosion, physics, and engineering mechanics. Schools receiving fundamental research grants in 1953–54 are: California Institute of Technology, Carnegie Institute of Technology, University of Chicago, Harvard, Massachusetts Institute of Technology, Princeton, University of Rochester, Stanford, and Yale.

Shell places no restrictions on publication of research results in this program or on the way the money is spent except that it be used directly for fundamental research in the field designated. This program was established in 1950 in recognition of the importance of basic research to industry and national defense and of the fact that although colleges and universities are well-equipped to carry on such research, they are often handicapped by lack of funds.

The Shell Fellowship Program is designed to help outstanding graduate students obtain advanced degrees in the fields of chemistry, chemical engineering, geology, geophysics, mechanical engineering, petroleum production engineering, physics, and plant science.

Shell fellows are selected by their colleges or universities and each fellow receives a stipend of $1,500 a year plus payment of tuition and fees. The school receives $400 for related research expenses of the fellow. Candidates in their last year of doctorate study are given preference, but awards may be made to other graduate students. The fellows are under no obligation to Shell.

Both the fellowship and the basic research programs are administered by the Shell Fellowship Committee, made up of senior executives representing Shell Oil Company, Shell Chemical Corporation, Shell Development Company, and Shell Pipe Line Corporation.

BILLINGS GEOLOGISTS TO MEET

The Billings Geological Society of Billings, Montana, will hold its fourth annual field conference during the first portion of September, 1953, in the Little Rocky Mountain Area of north central Montana. Headquarters and registration will be at Zortman, Montana.

Two full days will be given to the study of several excellent Little Rocky Mountain sections extending from the Pre-Cambrian upward to the Upper Cretaceous. This will include the type locality for the Lower Mississippian.

Due to lack of adequate housing facilities, the Society plans to establish a field camp near Zortman. All persons attending will be required to bring sleeping bags. Due to inadequate accommodations, the Society encourages the registration of men only, with participation limited to 200.

Paul McGovney, Geologist for Honolulu Oil Corporation at Billings, is General Chairman for the field conference. John M. Parker, Geologist for George Greer, Trustee, at Billings, is Editor.

All persons wishing to attend the field conference should write immediately to J. L. Cramer, Stanolind Oil and Gas Company, 526 Securities Building, Billings, Montana, to obtain registration blanks.

ATLANTIC REFINING COMPANY AWARDS

PHILADELPHIA, March 29—Fourteen universities and colleges in the South, Southwest and Middle West have accepted awards for fellowships or scholarships offered by The Atlantic Refining Company, it was announced today. The awards will cover the academic year beginning next September. The company stated that the awards were made for the purpose of encouraging outstanding undergraduate and graduate students in the study of techniques connected with crude oil production.

The studies specified in the awards will be carried on in a Department of Geology, Geophysics or Chemical, Petroleum, Mechanical or Electrical Engineering at the various institutions. Each university and college will recommend a student as the recipient of its Atlantic award on the basis of his scholastic accomplishments and promise in the department designated by the company.

The fellowships have been accepted by Washington University, St. Louis, Mo., and Rice Institute, Houston, Tex.

Scholarships have been awarded to the University of Texas, Austin; Southern Methodist University, Dallas; Texas A. & M. College, College Station; and Texas Technological College, Lubbock, Tex.; University of Oklahoma, Norman, and Tulsa University, Tulsa, Okla.; Louisiana State University, Baton Rouge, La.; New Mexico School of Mines, Socorro, N.M.; Ohio State University, Columbus, Ohio; Georgia Institute of Technology, Atlanta, Ga.; Colorado School of Mines, Golden, Colo. and St. Louis University, St. Louis, Mo.

Atlantic hopes through these awards to provide additional incentive and assistance to those students who show the greatest promise of success in the fields of science, engineering and research directly related to petroleum industry operations.

GOVERNMENT REPORT ON EMPLOYMENT OUTLOOK

The Bureau of Labor Statistics has announced publication of a report titled: "Employment Outlook for Earth Scientists," for the benefit of earth science students and for the use of occupational counselors and members of the professions concerned. Not only does the report list current earnings in each of the sciences, but describes the nature of work involved in each, where the scientists are employed, requirements for entering the professions, and probable employment trends. The professions covered are: geology, geophysics, oceanography, meteorology, and geography. (1951) 38 pages, with illustrations and charts. Order Catalog No. L 2.3:1050 (30 cents) from Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C.

AWARD FOR BEST PAPER OF 1952

The outstanding paper published in *Geophysics* during the year 1952 was "The Significance of Diffraction in the Investigation of Faults" by Theodor Krey, of Seismos GmbH, Hannover, Germany. This paper was published in the October issue of that year, and was chosen to receive the award by the Standing Committee on Honors and Awards. Represented by a certificate and plaque, the award was presented at the annual meeting in Houston by President Curtis Johnson, and was received for Mr. Krey by Ir. A. van Weelden, President of the European Association of Exploration Geophysicists.

THEODOR KREY

THE EUROPEAN ASSOCIATION OF EXPLORATION GEOPHYSICISTS

A total of 489 geophysicists in Western Europe and Africa now belong to the European Association of Exploration Geophysicists, according to the report of Ir. A. van Weelden, of Bataafsche Petroleum Mij., The Hague, first President of the Association. Mr. van Weelden, who as a member of SEG served last year as chairman of the European Program Committee, made this report to the SEG Council during the annual meeting in Houston last March.

The Association was inaugurated in The Hague in December, 1951, and since that time three meetings have been held, the last of which was in Paris last May. At Hannover, in December, 1952,

the Association voted to issue a quarterly publication entitled *Geophysical Prospecting*. Mr. van Weelden distributed copies of the first issue (March, 1953) at the Annual Joint Council meeting.

At the close of the SEG annual meeting Mr. van Weelden met with the Executive Committee to draw up terms for affiliation of the two societies, and returned to The Hague with an SEG proposal for submittal to the EAEG at its May meeting. Designed to promote a wider exchange of geophysical literature and "know-how," the proposal also provides that publications of the two groups would be available to members of both at reduced rates.

Membership in the EAEG is available to members of the SEG upon application. Forms may be obtained from the SEG business office. For information on membership dues and subscription prices, write to Dr. B. Baars, Bataafsche Pet. Mij., 30 Carel van Bylandtlaan, The Hague, Netherlands. Dr. Baars can also furnish rates for advertising in *Geophysical Prospecting*.

MINUTES OF ORGANIZATIONAL MEETING
HOUSTON STUDENTS SECTION, S.E.G.

A meeting was held at 6:00 P.M., Friday, May 22, 1953 at Weldon's Cafeteria to organize the Houston Students Section of the Society of Exploration Geophysicsts. Twenty-one students attended. These were: Jack R. Smith, Edward H. Urquhart, B. J. Johnson, J. C. Cubria, T. D. Baulch, J. J. Shipps, Jesse C. Haver, F. L. Sachnik, Lynn W. Brasher, Wm. G. Thorsen, V. E. Child, W. D. West, A. L. "Rocky" Eaton, Thomas F. Vining, Dwight E. Davis, Norvel L. Miller, Sam B. Ray, Bert L. Bass, Jack L. Wright, Howard J. Caillouet, and William E. Allen.

Dr. T. N. Hatfield, Chairman of the Physics Department, and Dr. R. A. Geyer, of the Geological and Physics Departments, represented the University of Houston as sponsors of the Student Section. Colonel E. S. Waters, Chairman of the Department of Electrical Engineering, of Rice Institute represented that school in the absence of Professor Carl Wischmeyer, who was unable to attend. No students from Rice Institute were present at this meeting as, unfortunately, the meeting was conflicted with examination period at Rice. J. E. (Sam) McGee, President of the Houston Section of the S.E.G., represented that society, and N. C. Steenland represented the national S.E.G., on behalf of Eugene Frowe, Chairman of the Committee on Student Affairs, who was unable to attend.

Mr. William E. Allen was elected temporary chairman of the Student Section and Mr. William G. Thorsen, temporary secretary. The Chairman appointed a Constitutional Committee with Mr. F. L. Sachnik as Chairman. He also appointed a Nominating Committee under the chairmanship of Mr. Edward H. Urquhart. Mr. Jesse C. Haver and Mr. Jack L. Wright agreed to serve on the nominating committee. In addition, Colonel Waters agreed to select a Rice Institute student to serve on the two committees.

The group instructed the Constitutional Committee to begin immediately to prepare the constitution and to call a meeting of the group during the summer to adopt the constitution.

Colonel Waters reviewed the activities during the past year of a similar society at Rice Institute, The Engineering Society. That group was addressed four times by representatives of various engineering industries on vocational guidance. Dr. Hatfield pointed out that there were several discussions during the past year on instituting a geophysical curriculum at the University, so he was particularly pleased to see this student section organized at this time. Dr. Geyer voiced the need of a student section and pledged his support to its activities. Mr. McGee pledged the complete cooperation of the Houston Section of the S.E.G. which had already begun by way of their underwriting the cost of the organizational banquet. Dr. Steenland, as a member of the Houston Section, expressed a desire for a very concrete program of assistance to the Student Section, mentioning, for example, "Scholarship Assistance" and "Best Paper Contests" similar to that held each year by the Houston Geological Society.

The meeting was adjourned after the group gave a vote of thanks to the Houston Section of the S.E.G. for underwriting the cost of the dinner.

NELSON C. STEENLAND

AMERICAN GEOLOGICAL INSTITUTE

The American Geological Institute, through the good offices of its member societies and the editors of geological journals, is beginning a compilation of geological abstracts. The first issue will

cover January to June 1953, and will be circulated to subscribers about July 15. Thereafter the issue will be quarterly scheduled as March 30, June 30, September 30, and December 30 of each year.

The subscription price will not exceed $2.00 per year. So that the editors may anticipate printing requirements, will all geophysicists interested in subscribing to the new service, send a postal card at once to: American Geological Institute, 2101 Constitution Avenue, N.W., Washington 25, D. C. *Do not send any subscription money now.*

PERSONAL ITEMS

Members of the Society are invited to notify the business manager, in care of the SEG, at 624 South Cheyenne, Tulsa 3, Oklahoma, of any change in their positions or companies for announcement in this section of their *Journal*. Members are further invited to check with the public relations departments of their companies to assure that *Geophysics* is on their mailing lists to receive publicity releases.

THE REV. JAMES B. MACELWANE, St. Louis University, was elected President of the American Geophysical Union for the three-year period 1953–56, it was announced at the Annual Meeting of the Union on May 4. PROFESSOR MAURICE EWING, Columbia University, was elected Vice-President.

The election of PROFESSOR HUGO BENIOFF of the Seismological Laboratory, California Institute of Technology, to the National Academy of Sciences has been announced by the Academy at its Spring meeting in Washington, D. C. Election to this body constitutes one of the highest honors that can be conferred upon a scientist in this country. Only seven other members of the S.E.G. have been elected to this organization.

THE DALLAS GEOPHYSICAL SOCIETY has placed an order for a complete 3-component, long and short period Benioff seismometer. It is to be installed at the new Seismological Station which is being established at Southern Methodist University. The Dallas Society has raised the funds for this equipment, having contributed part of the necessary amount from its own treasury.

LEROY SCHARON, Associate Professor of Geology, Washington University, was recently appointed to the Executive Committee of the Mining, Geology and Geophysics Division of the American Institute of Mining and Metallurgical Engineers. At the annual meetings of the Institute, held in Los Angeles during February of this year, he was elected Chairman of the Mining Branch and a member, ex-officio, of the Board of Directors for the year 1953.

CURTIS H. JOHNSON has joined the staff of GSI as manager of the newly-formed GSI Marine Division. His headquarters are in Dallas, at offices of Geophysical Service Inc., 6000 Lemmon Avenue.

Mr. Johnson was president of the Society of Exploration Geophysicsts in 1952–53. He is also a member of the American Association of Petroleum Geologists and of the American Geophysical Union. He has moved to Dallas from Los Angeles, where he was assistant chief geophysicist for General Petroleum Corp.

KAZIM ERGIN, formerly chief geophysicist at M.T.A. Enstitüsü, is now the acting director of the geology department of the same institute. He was also elected the vice-president of the Geological Society of Turkey during the annual meeting held in Ankara, last February.

JOHN F. PARTRIDGE, JR., District Exploration Superintendent at Casper, Wyoming and associated with The California Company for eleven years, has resigned to open practice as a Consulting Geologist-Geophysicist in the Rocky Mountain Area with offices at Room 211, O-S Building, Casper, Wyoming.

C. NEWTON PAGE has joined the Continental Geophysical Company to manage their West Texas division office in Midland, Texas. Mr. Page recently resigned as seismologist for the Honolulu Oil Corporation, Midland.

Establishment of a subsidiary company at Salt Lake City, Utah, to serve expanding mapping requirements in the West, has been announced by Aero Service Corporation of Philadelphia. The subsidiary, Aero Service Corporation (Western), will compile topographic maps and photomaps

for oil and mining companies located in the west, as well as produce maps for highways, cities, flood control, irrigation studies, and other engineering uses.

Aero Service Corporation (Western) will employ the same mapping methods and equipment as the parent company.

REESE H. TUCKER, manager of the Land-Geological division of Cities Service Oil Co., Bartlesville, Oklahoma, and District Representative for the Tulsa Section of the Society, has been elected vice-president of his company.

IRA H. CRAM has been named senior vice president of Continental Oil Co., Houston, Texas.

ROBERT L. KIDD, Bartlesville, Oklahoma, has been elected president of Arkansas Fuel Oil Corp., a recently-formed company. He was formerly vice-president of Cities Service Oil Co., in charge of oil and gas exploration and production.

H. M. HOUGHTON, formerly geophysical supervisor for Amerada Petroleum Corp., has become director and general manager of Geophysical Prospecting Co. of Canada, Ltd., Calgary.

CHARLES E. RIDDELL has become exploration manager for the northwestern division of British-American Oil Producing Co., with offices in Denver, Colo.

ELMER W. ELLSWORTH, assistant business manager of the American Association of Petroleum Geologists since 1946, has become business manager, succeeding J. P. D. HULL who has been appointed to the recently created position of managing editor.

STANLEY W. TOTTEN has been appointed division exploration superintendent of the Southeastern Division of The California Company.

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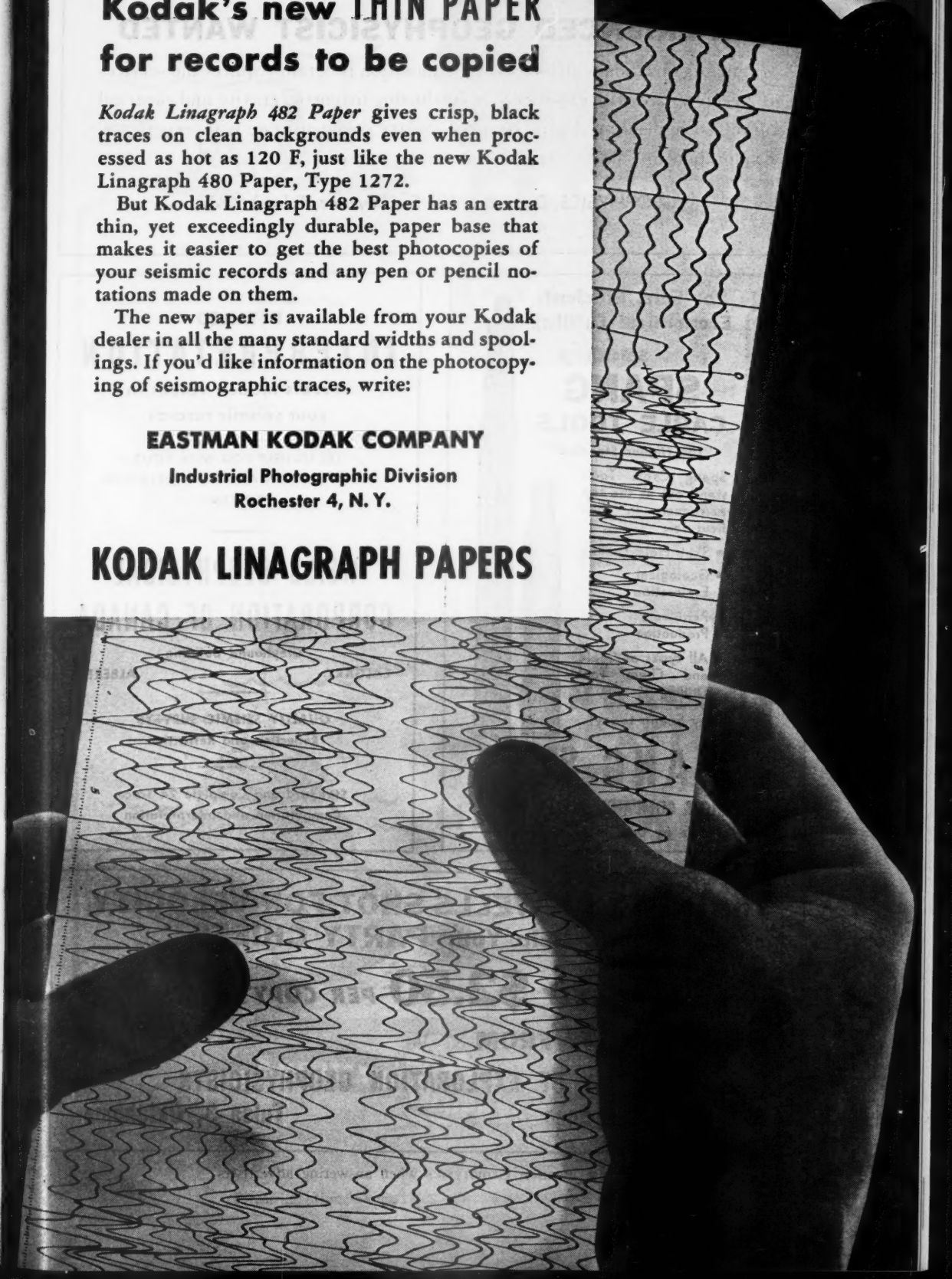

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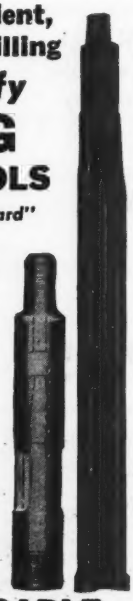

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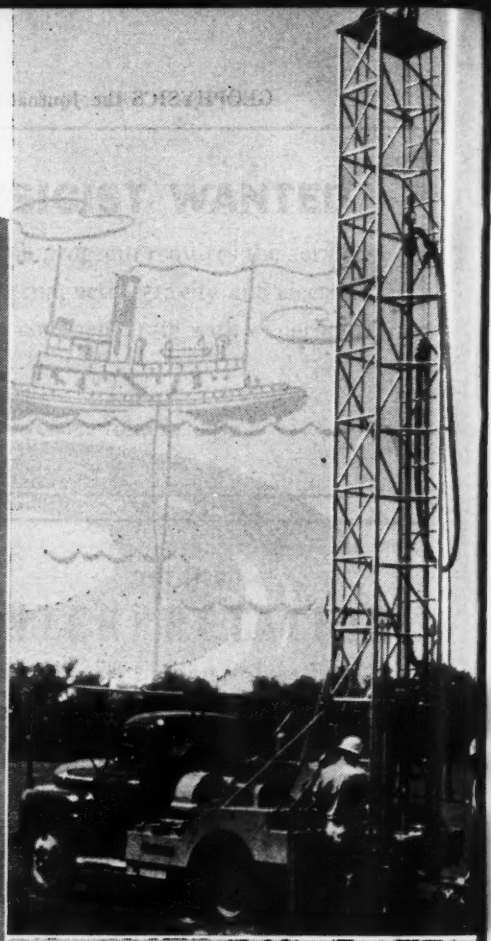

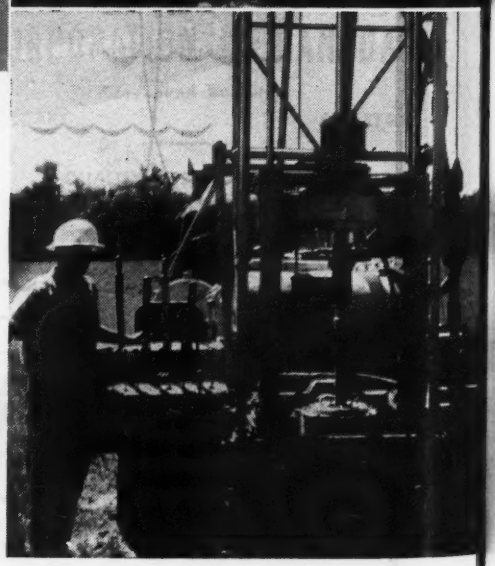

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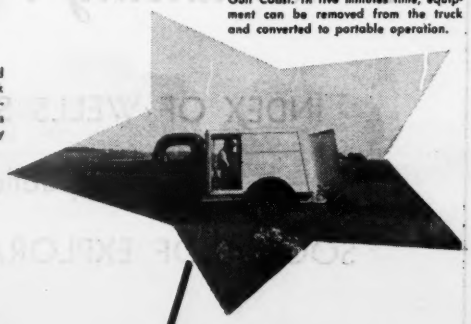

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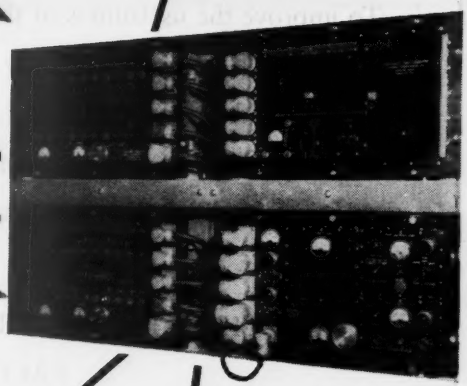
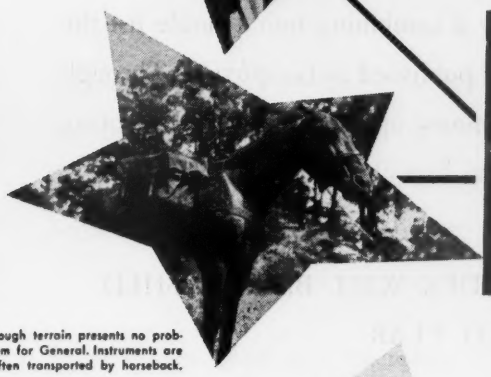
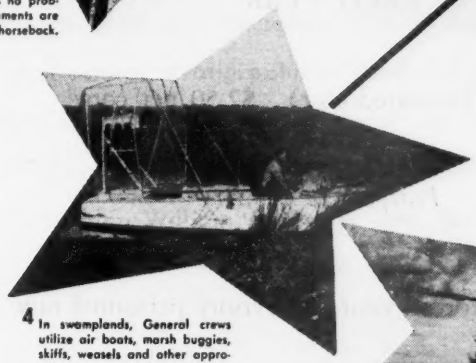


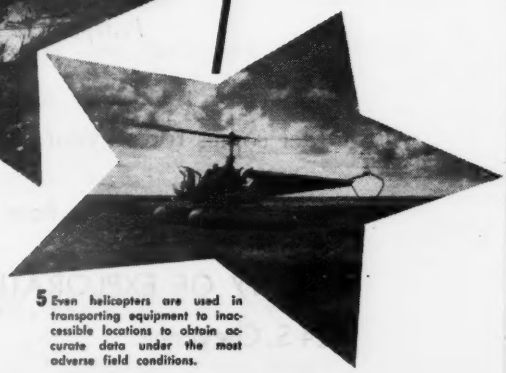
Instruments as normally installed in truck



3 Rough terrain presents no problem for General. Instruments are often transported by horseback.



4 In swamplands, General crews utilize air boats, marsh buggies, skiffs, weasels and other appropriate means of transportation.



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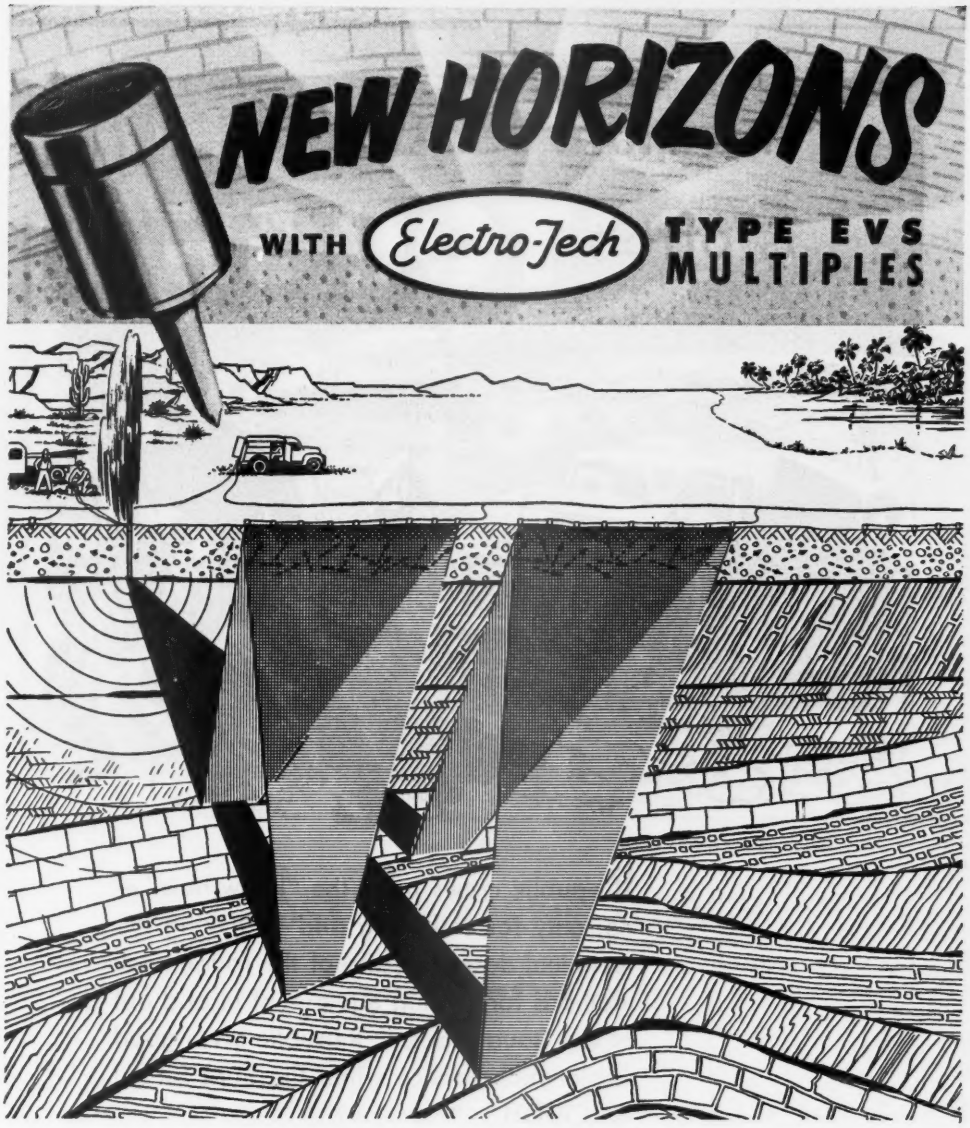

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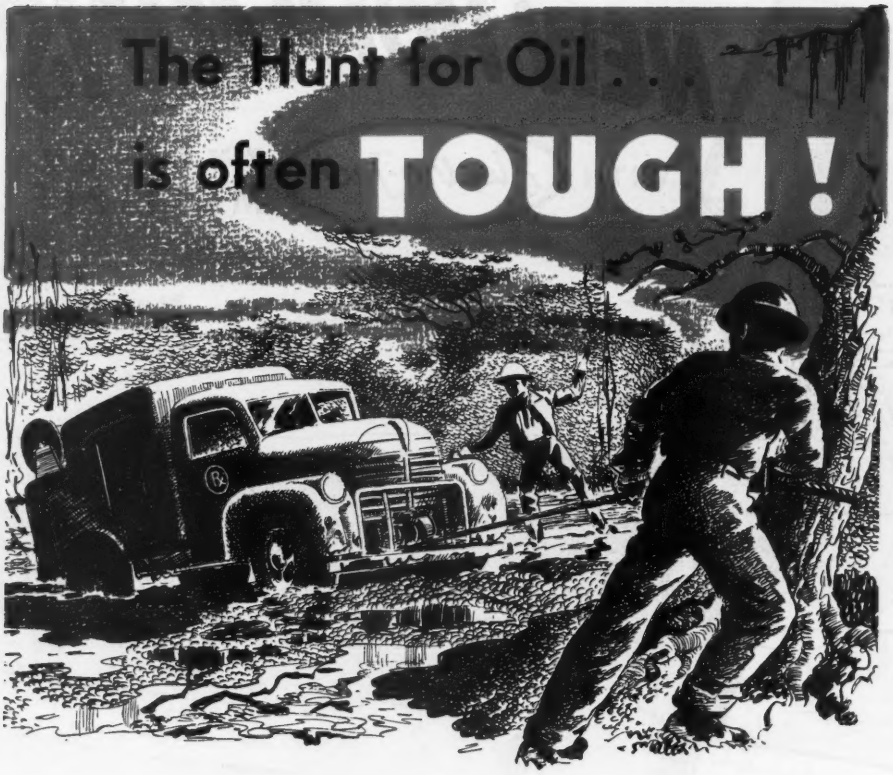

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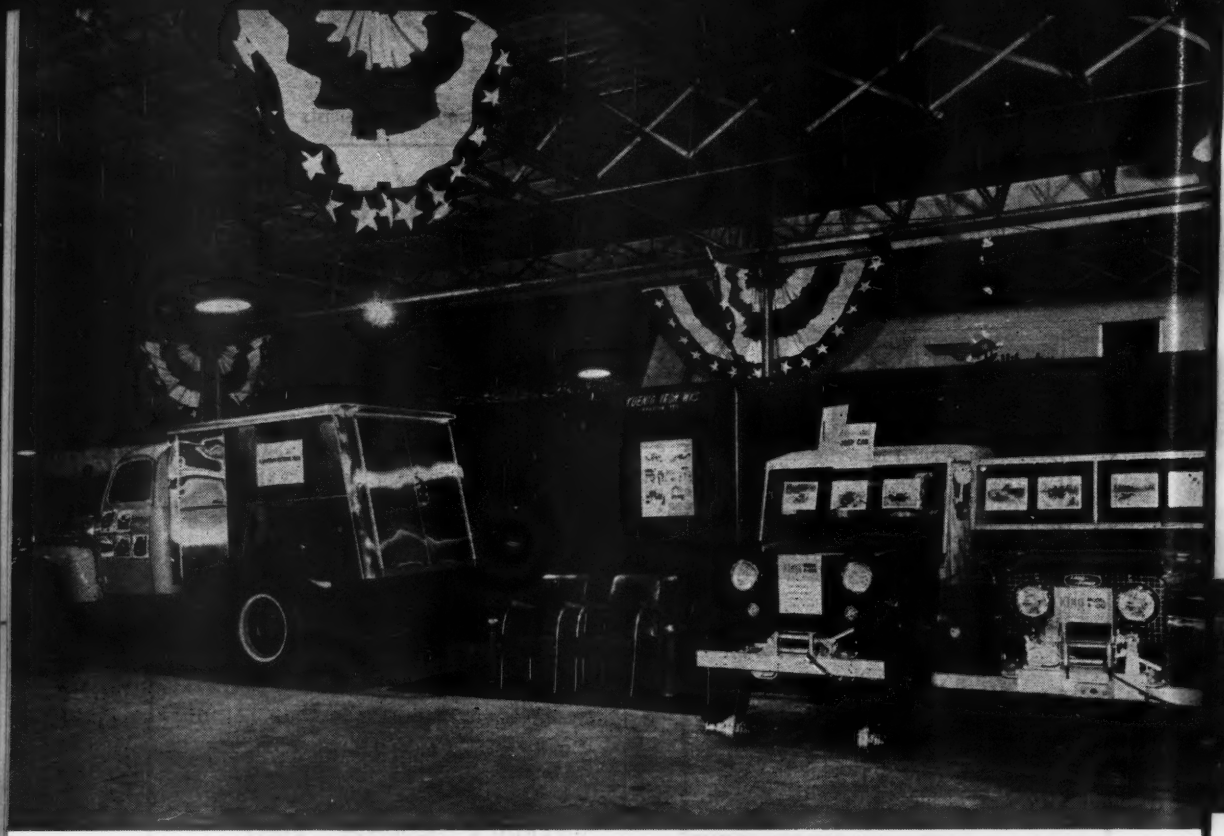

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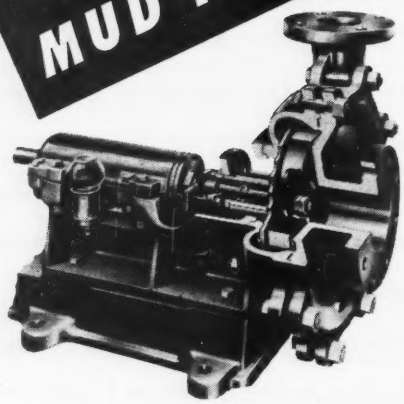

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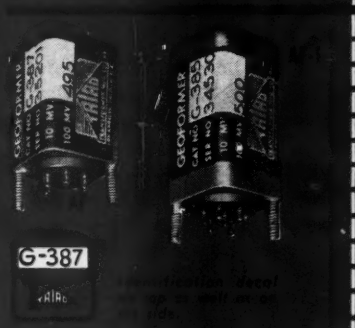

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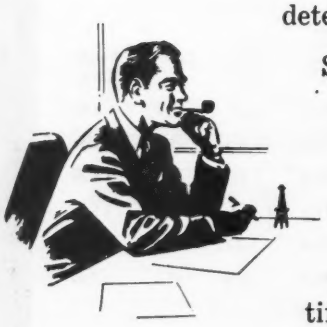

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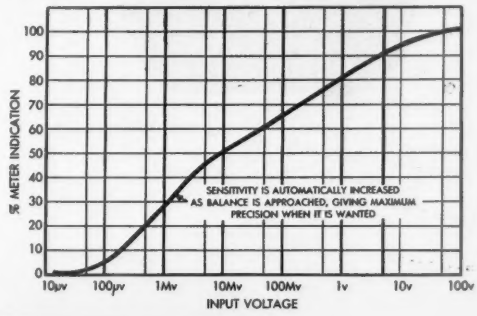

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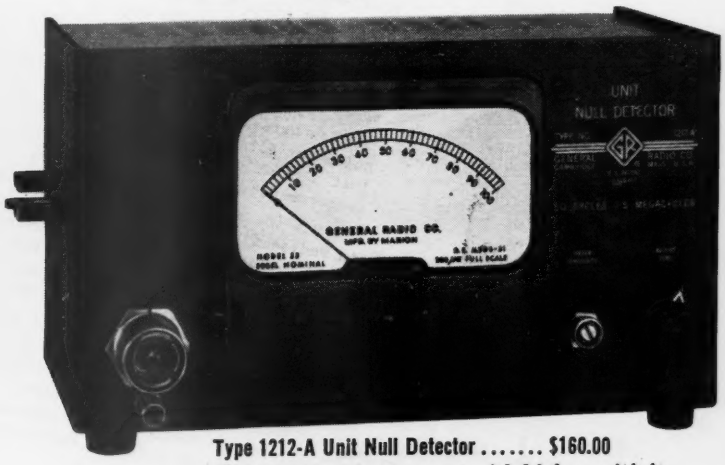

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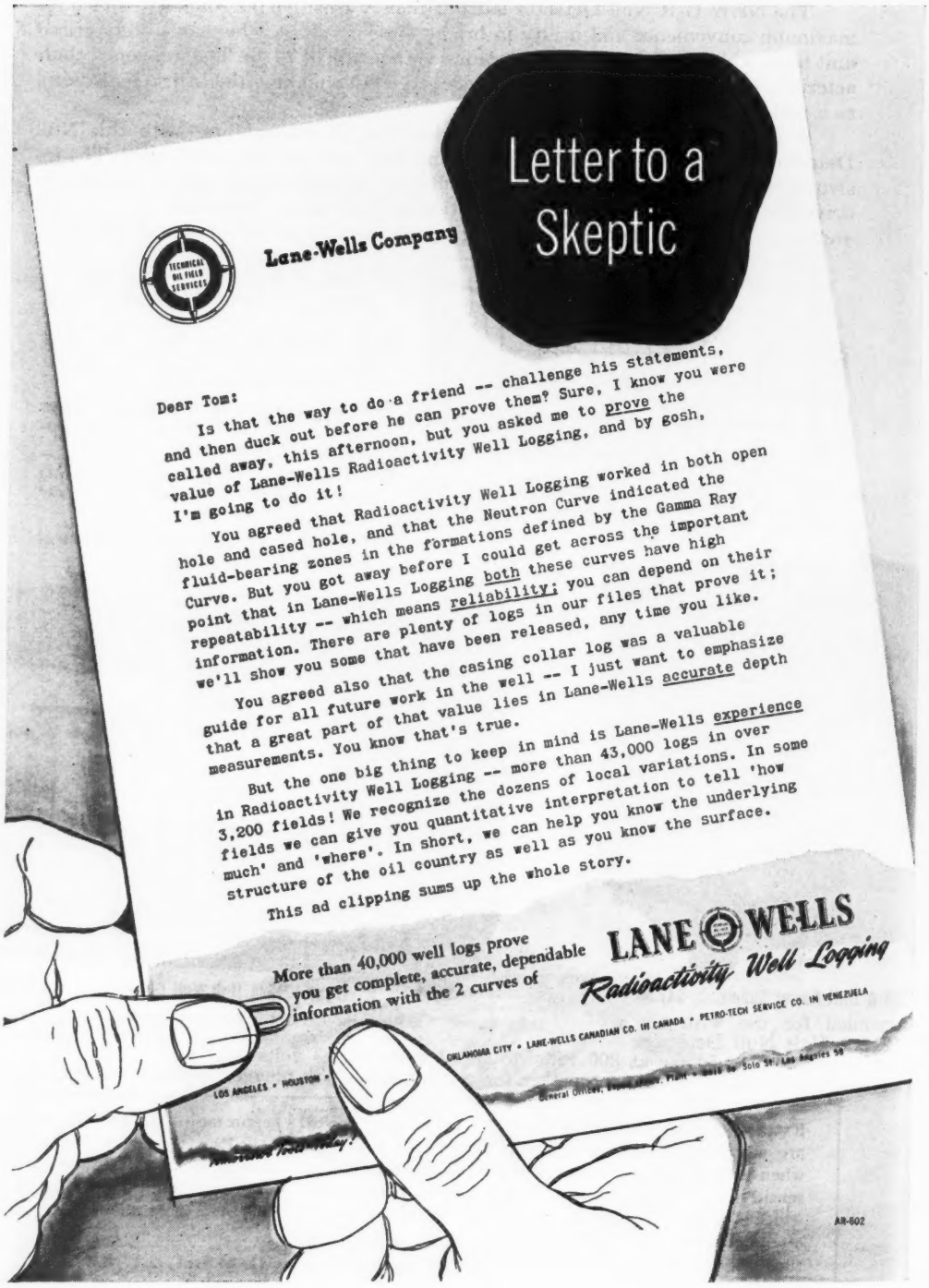
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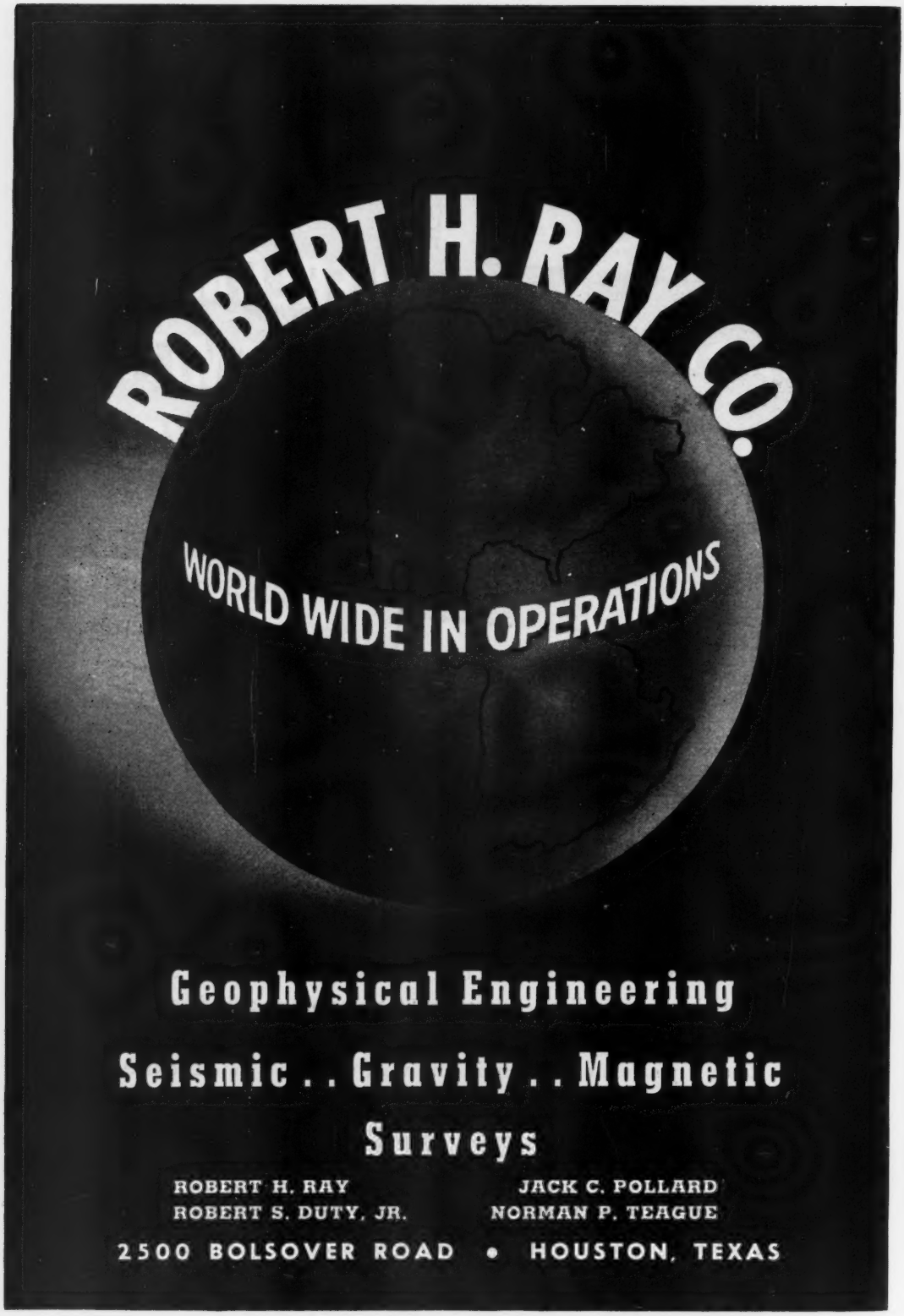

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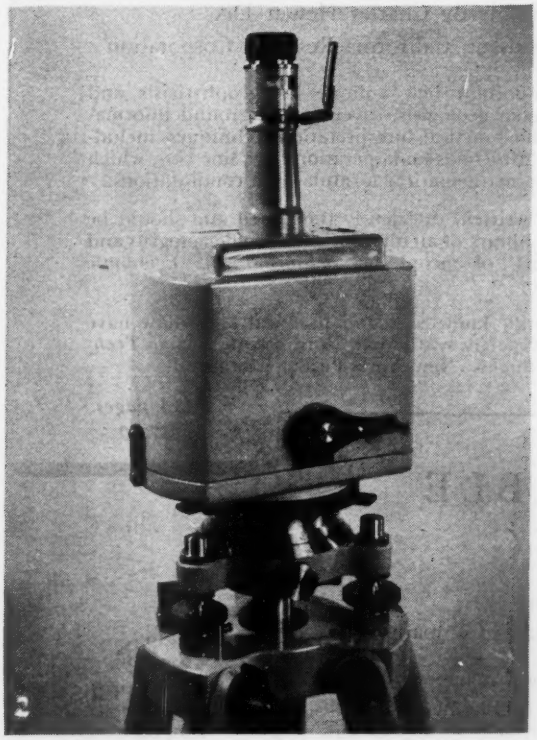

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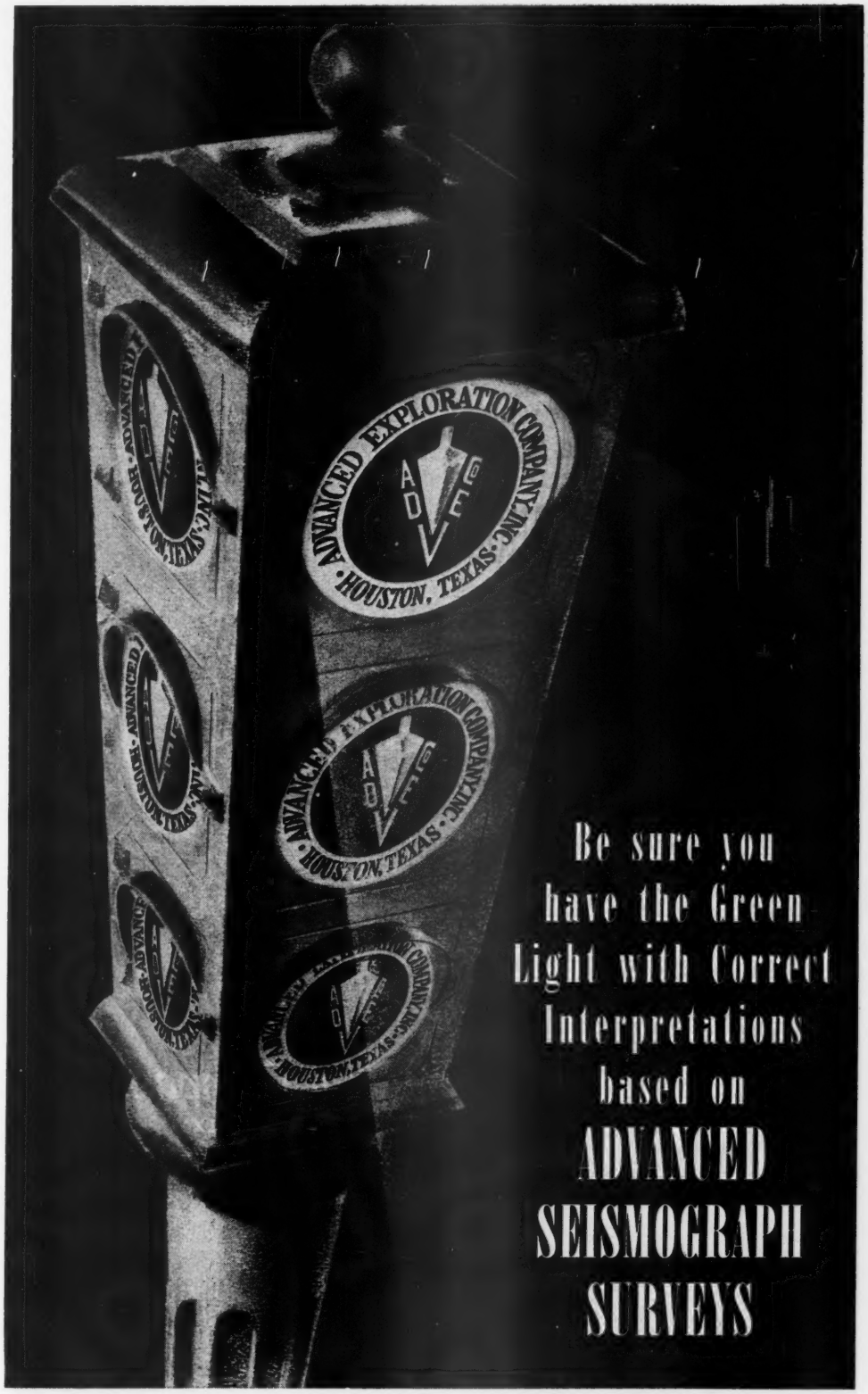
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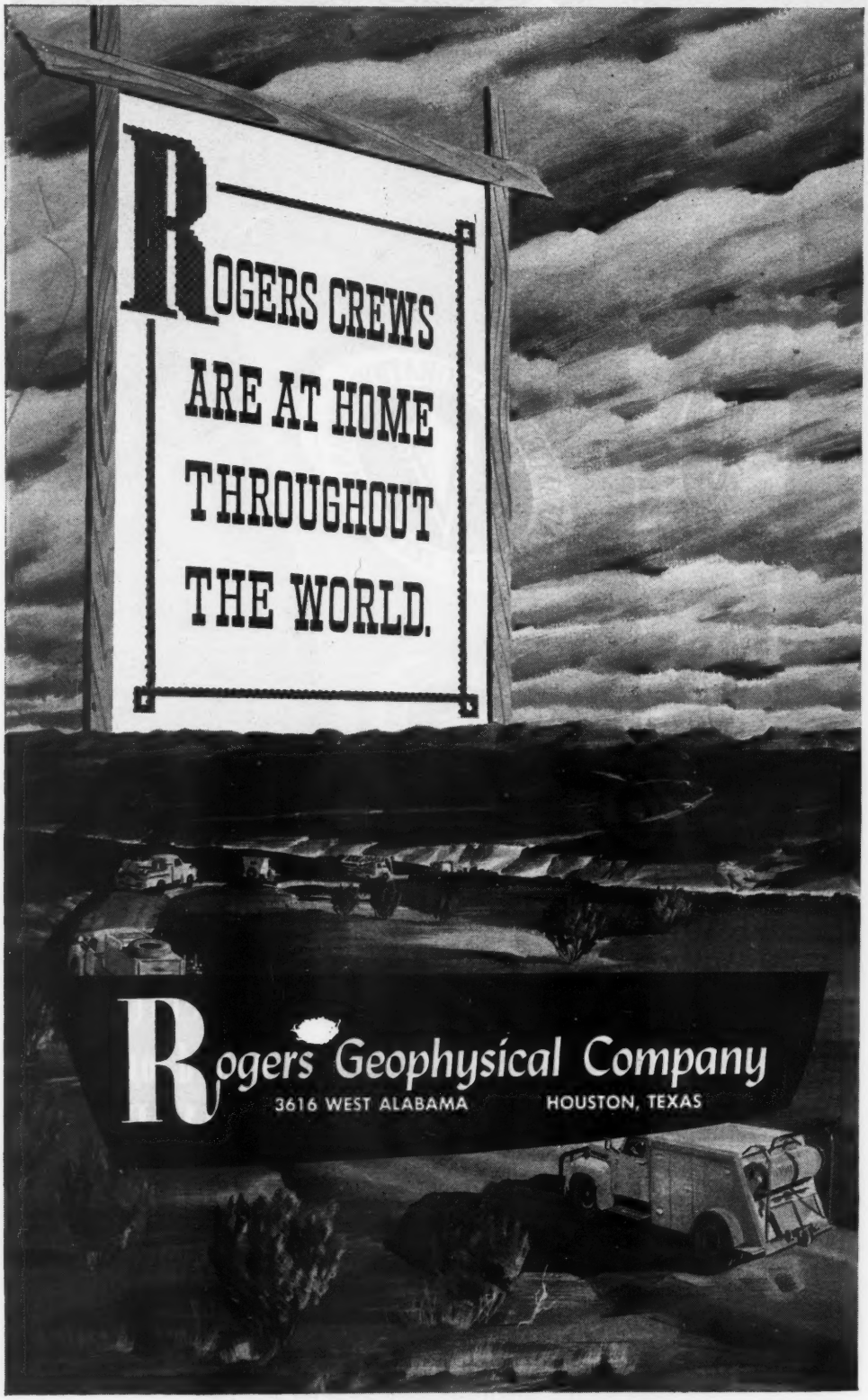
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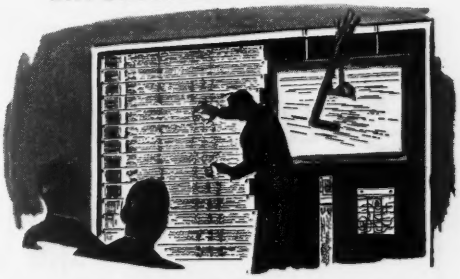

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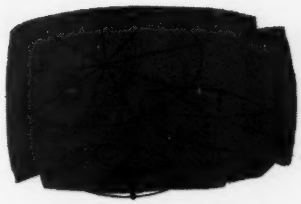

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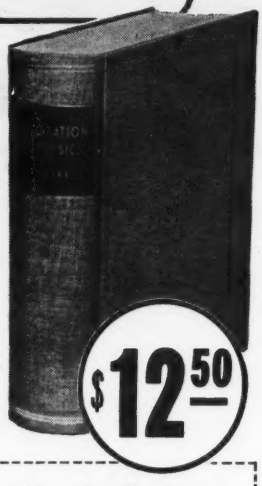

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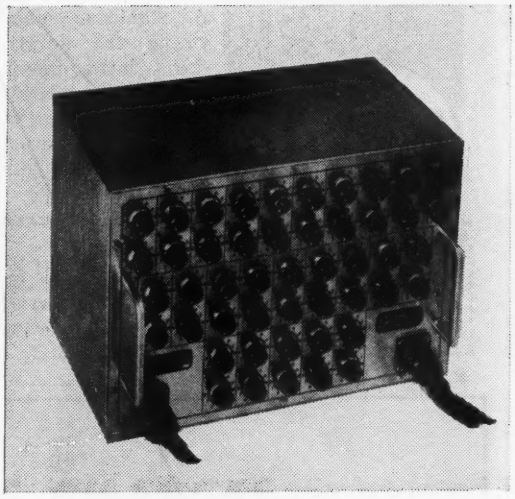

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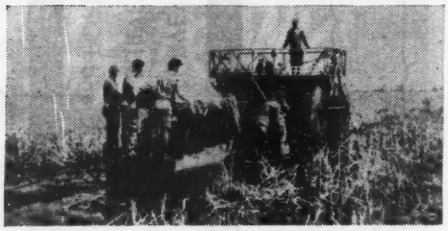

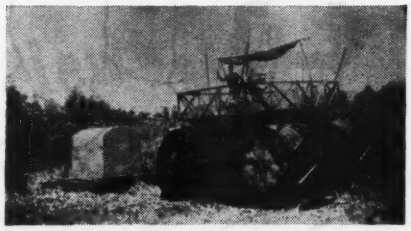

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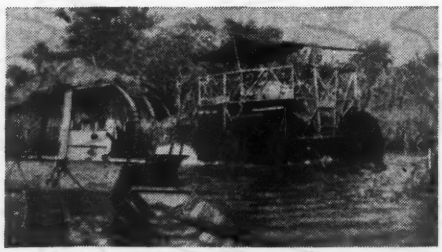

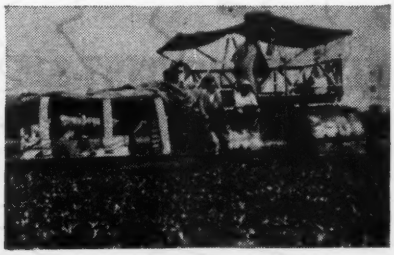

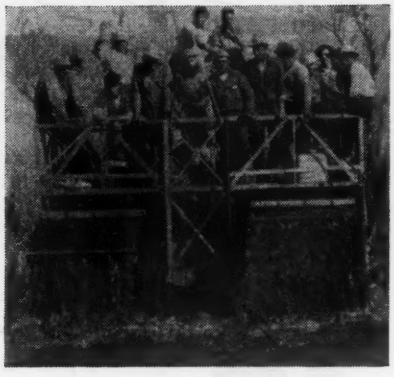

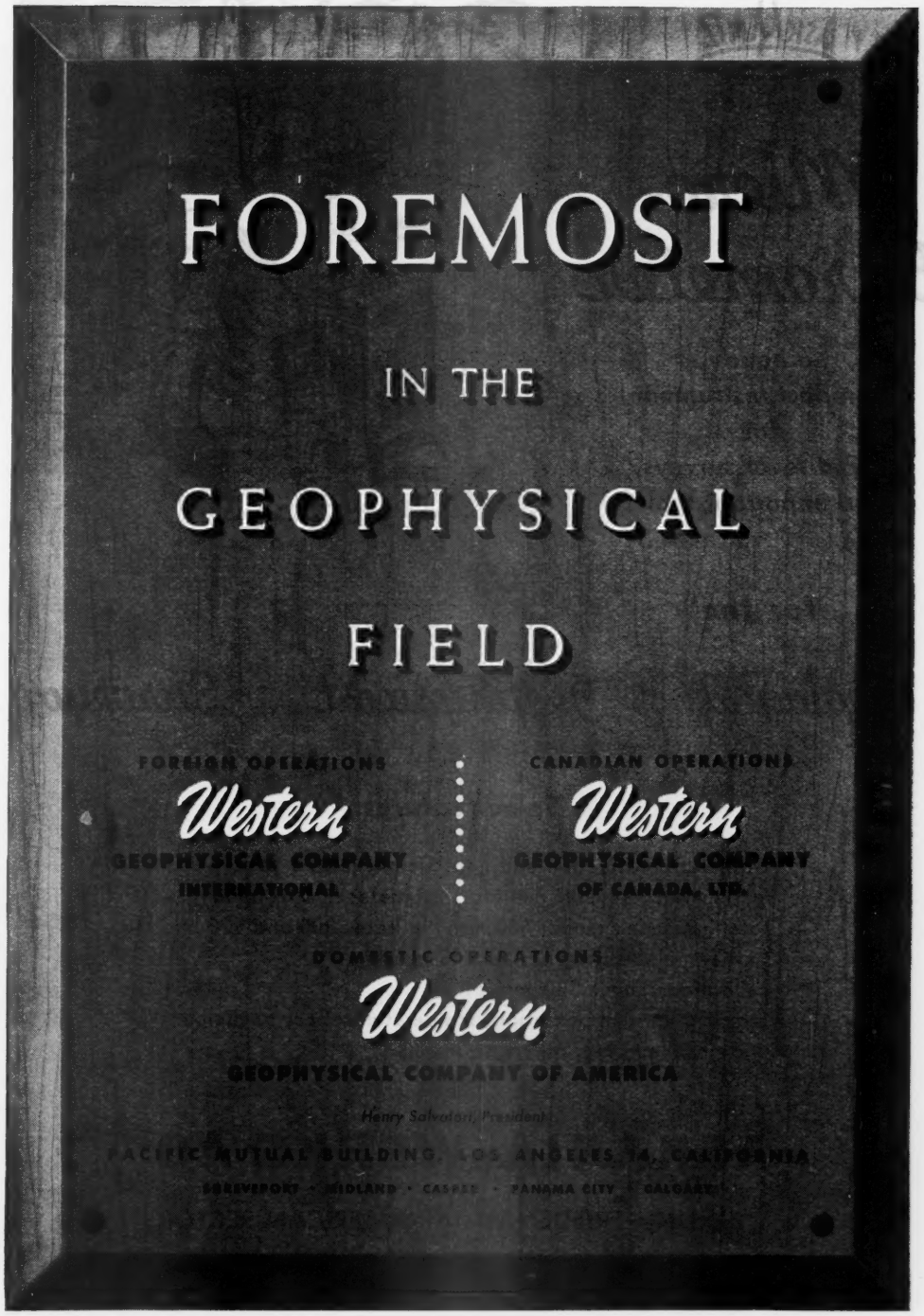
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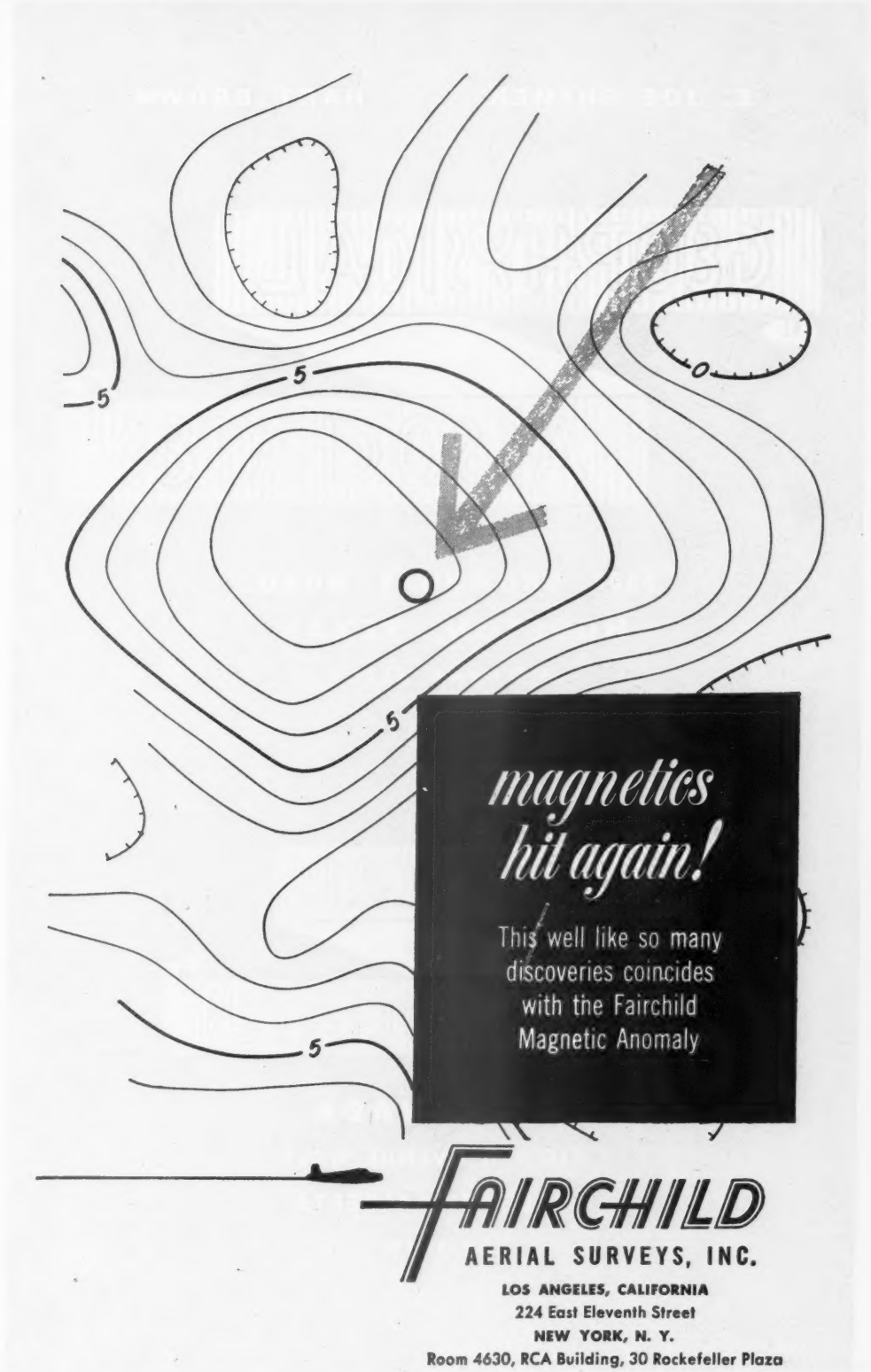

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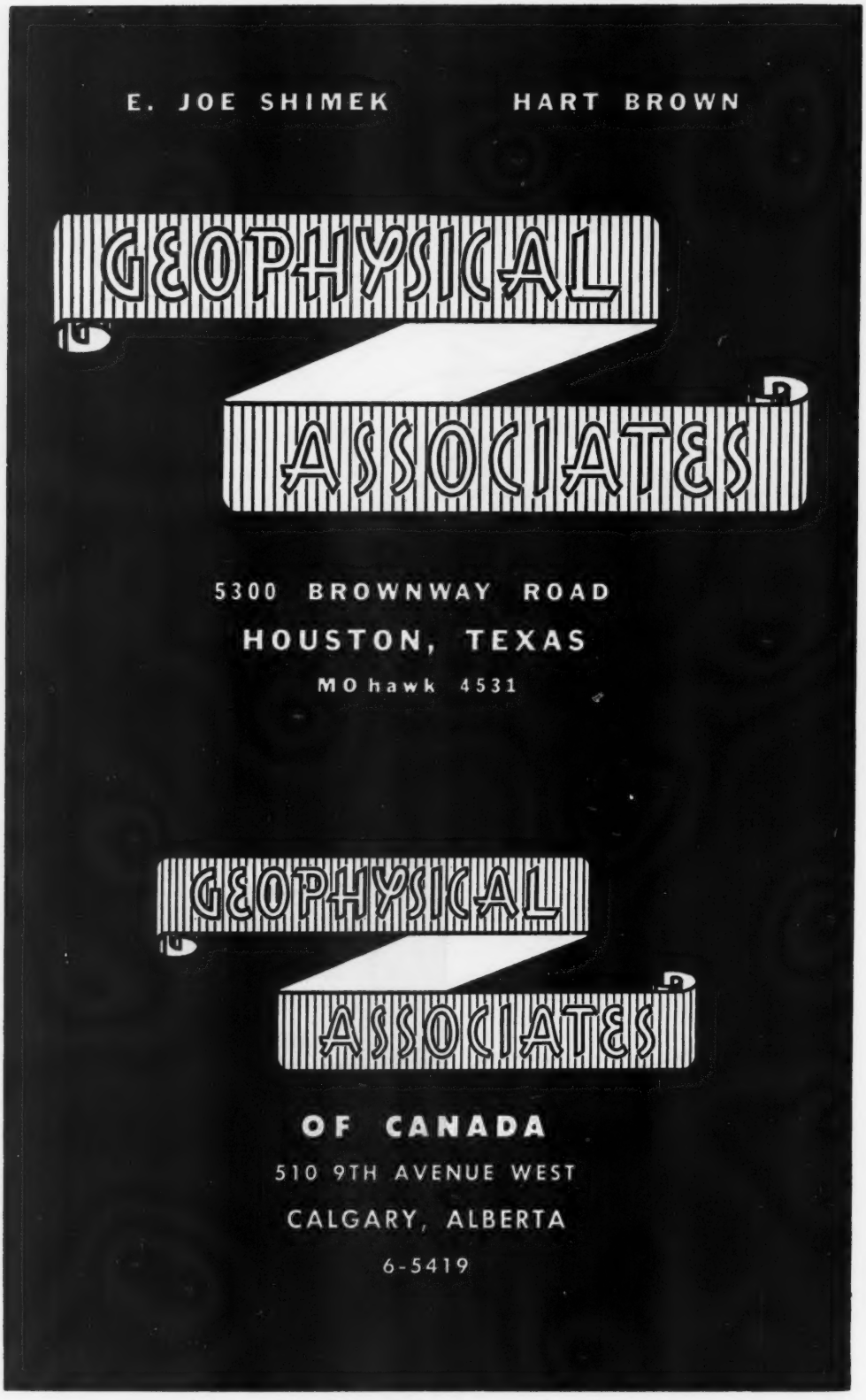
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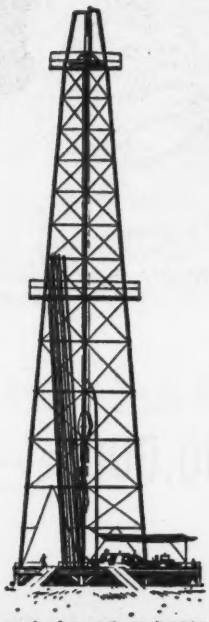

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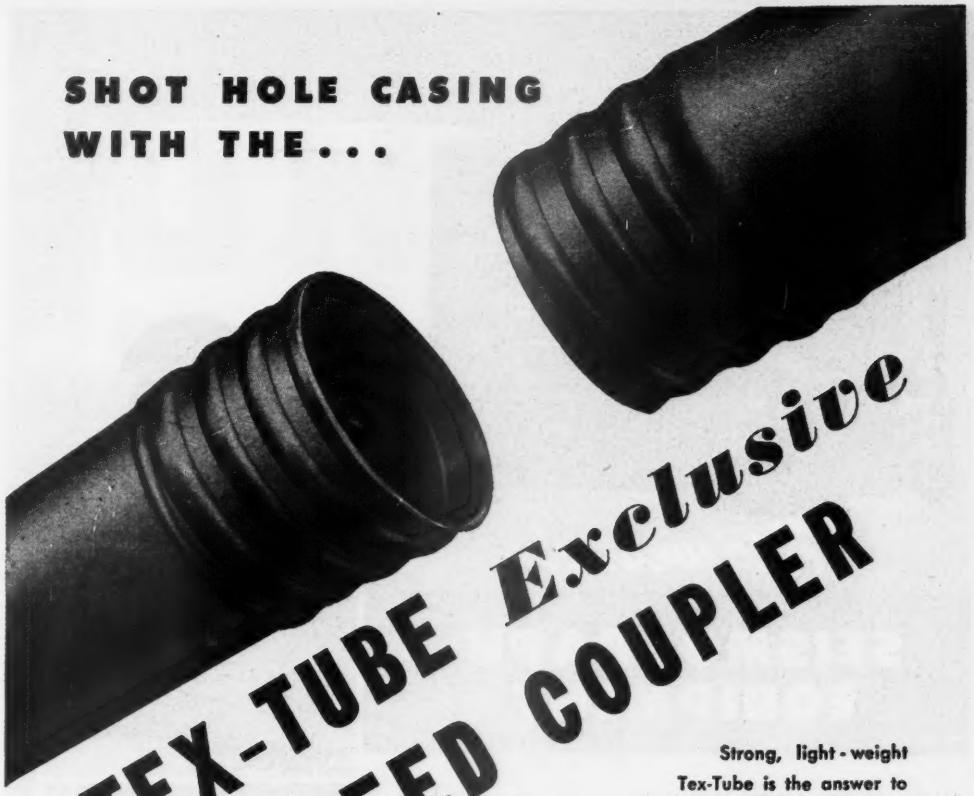

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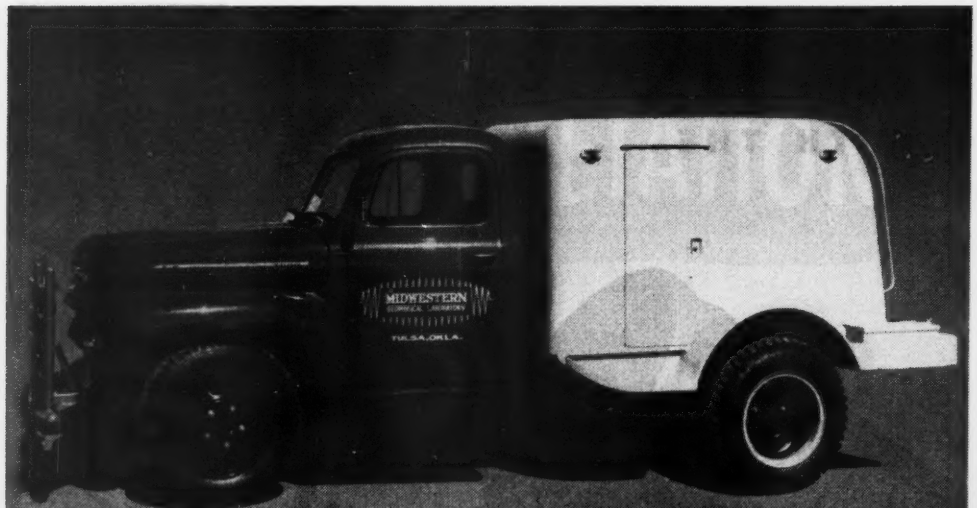

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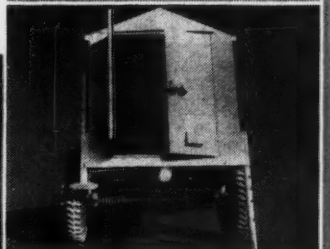

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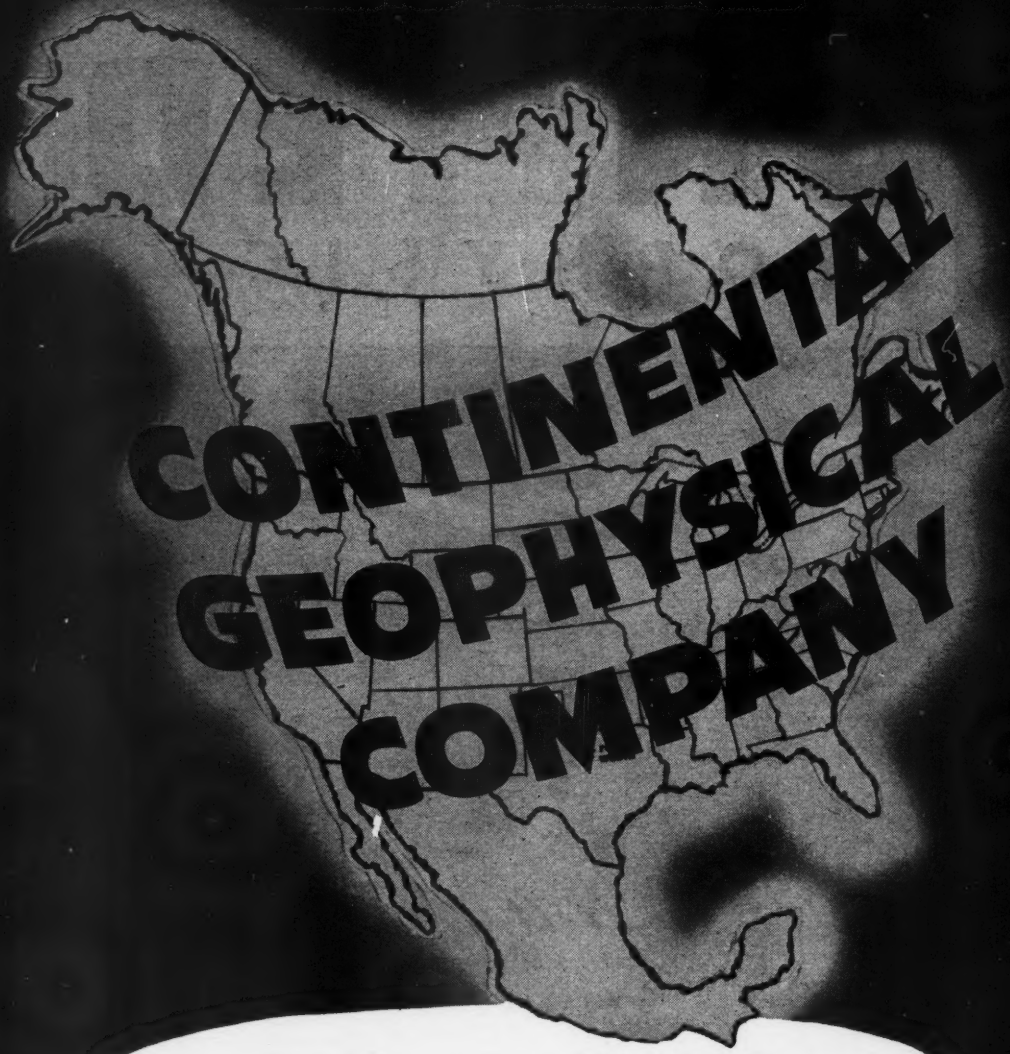

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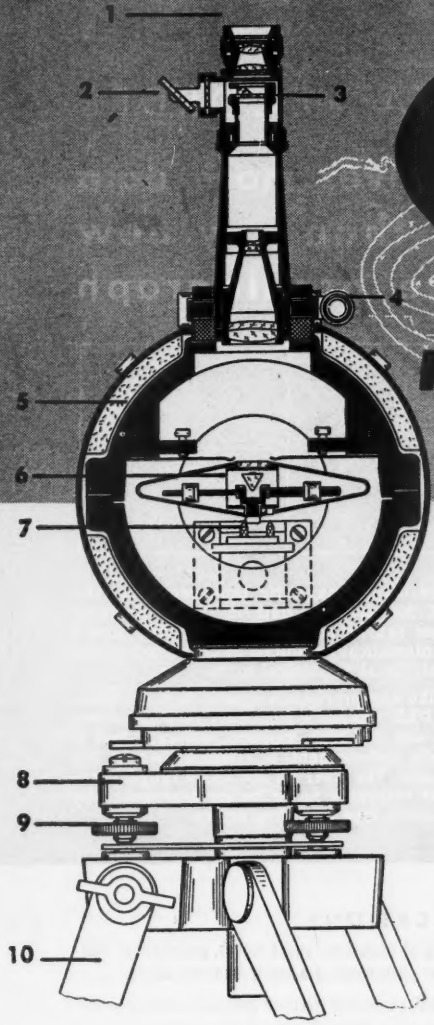

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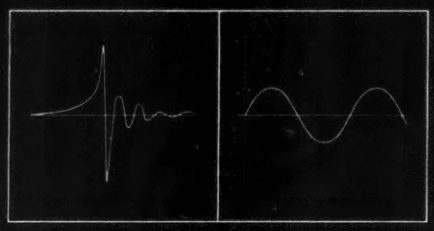

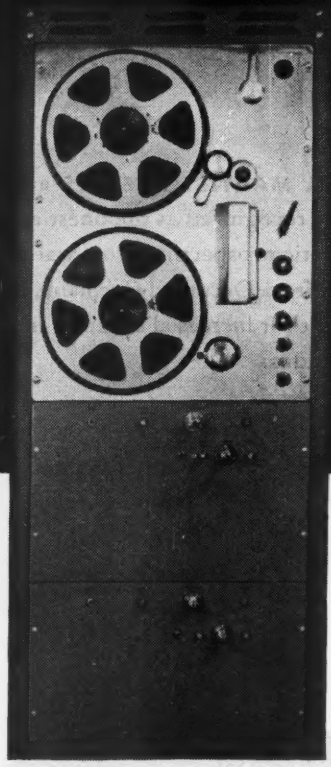

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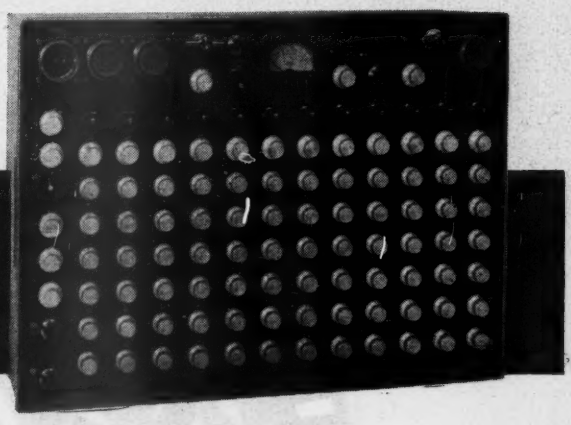

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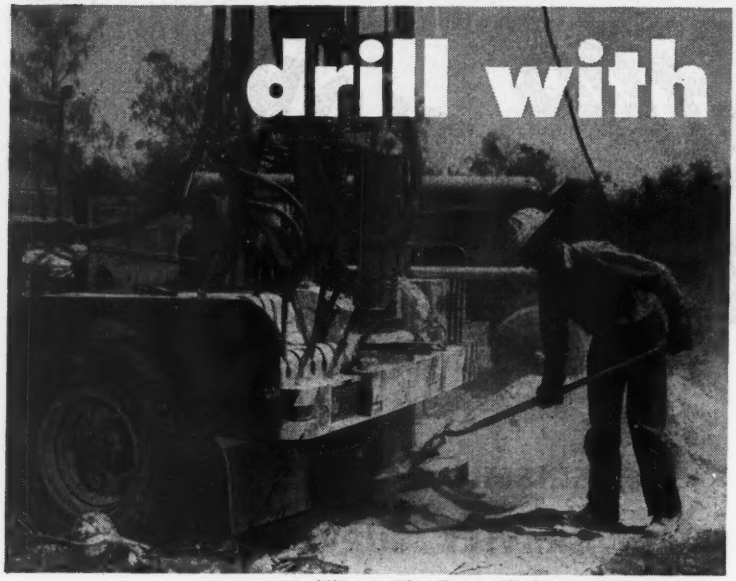

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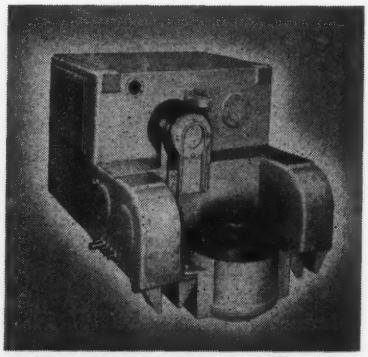

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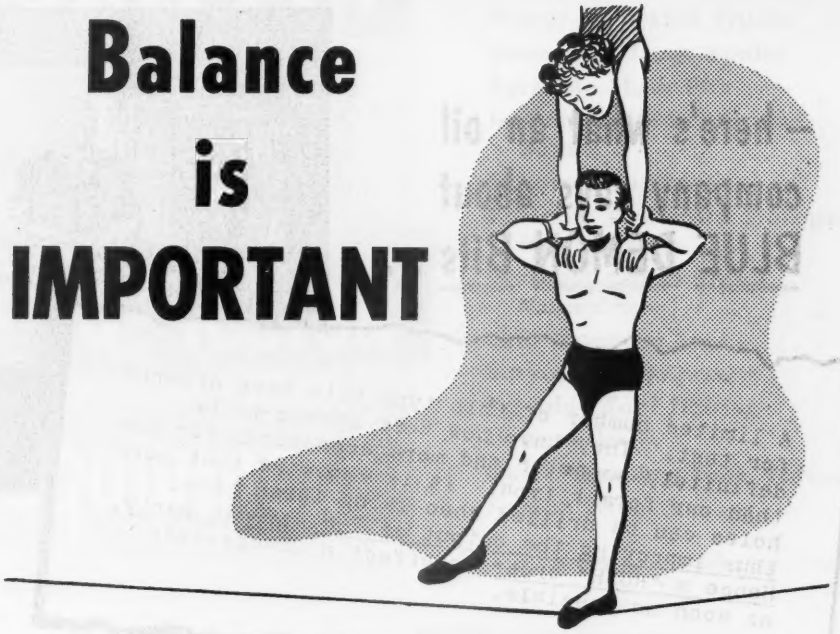

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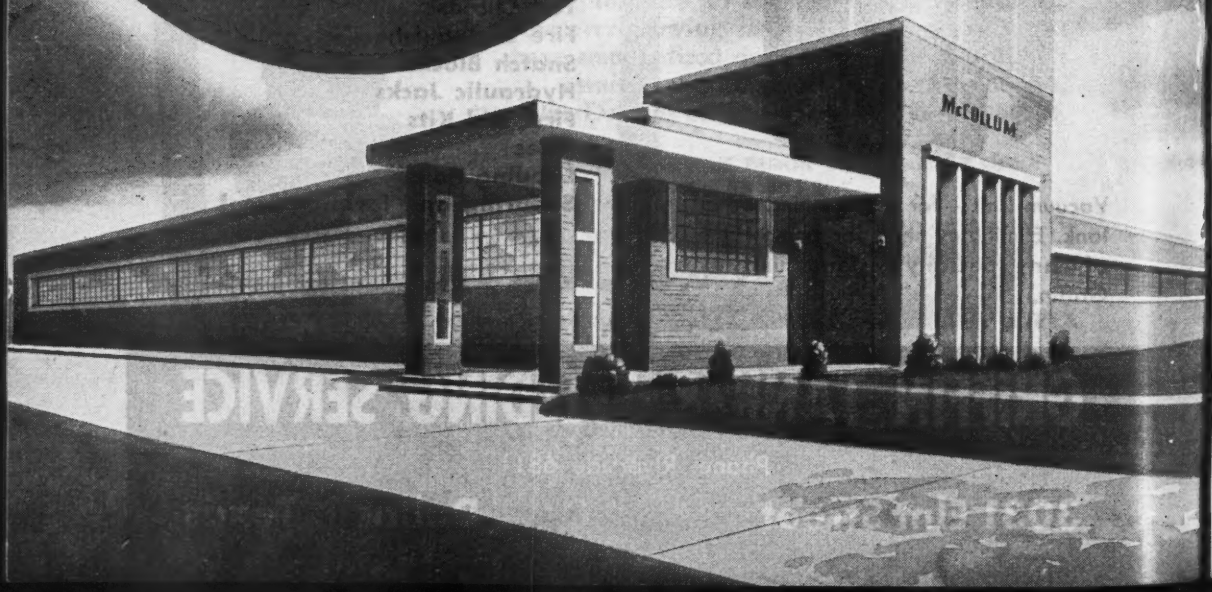

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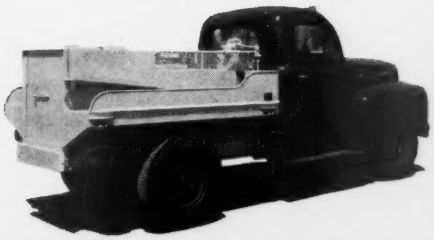
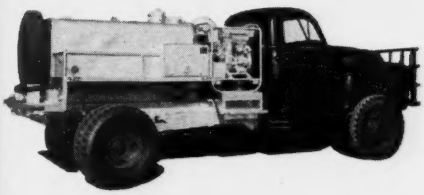


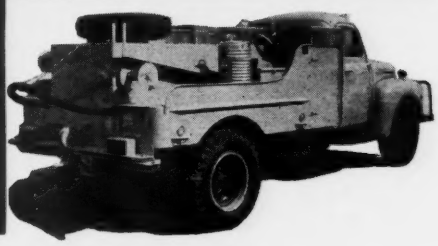
Lightweight shooting body mounted on Ford F-3 Truck . . . 110 gallon water capacity . . . 400 lb. powder magazine.

Special water purification water plant mounted on Coleman 4-wheel drive Chevrolet Truck . . . 600 gallon water capacity.



F-56 shooting body mounted on Dodge 2-ton Truck . . . 340 gallon water capacity . . . 600 lb. powder magazine.

Shooting Body mounted on Ford F-7 Truck . . . 600 gallon water capacity . . . 1000 lb. powder magazine.



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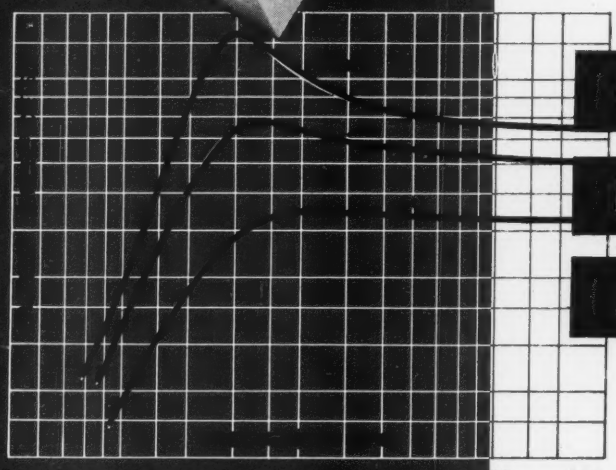

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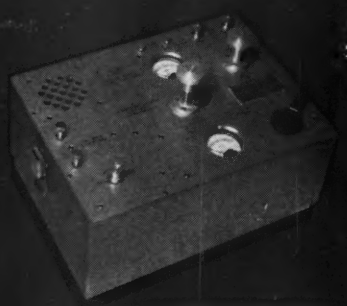

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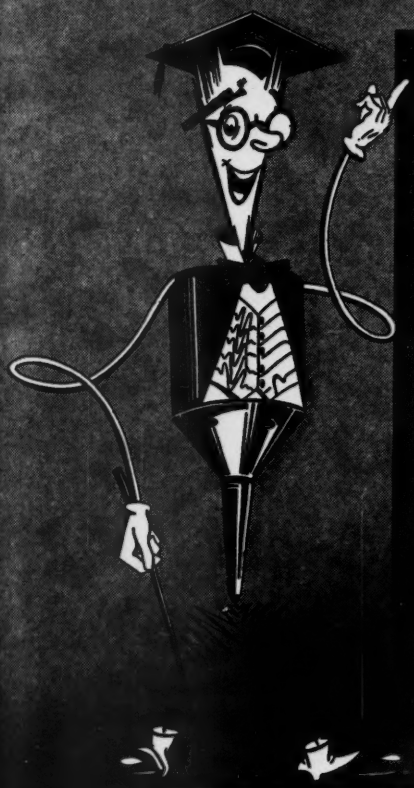

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- Number of shot holes
- Positioning of geophone spread
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- Arrangement of geophones
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